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(54) Title: ATOMIC LAYER DEPOSITION SYSTEM AND METHOD

(57) Abstract:

ATOMIC LAYER DEPOSITION SYSTEM AND METHOD

FIELD OF INVENTION

The present invention relates to advanced thin film deposition apparatus and methods used in semiconductor processing and related technologies.

BACKGROUND

As integrated circuit (IC) dimensions shrink, the ability to deposit conformal thin film layers with excellent step coverage at low deposition temperatures is becoming increasingly important. Thin film layers are used, for example, as MOSFET gate dielectrics, DRAM capacitor dielectrics, adhesion promoting layers, diffusion barrier layers, and seed layers for subsequent deposition steps. Low temperature processing is desired, for example, to prevent unwanted diffusion of shallow junctions, to better control certain reactions, and to prevent degradation of previously deposited materials and their interfaces.

The need for conformal thin film layers with excellent step coverage is especially important for high aspect ratio trenches and vias, such as those used in metallization layers of semiconductor chips. For example, copper interconnect technology requires a continuous thin film barrier layer and a continuous thin film copper seed layer to coat the surfaces of trenches and vias patterned in an insulating dielectric prior to filling the features with copper by electrochemical deposition (ECD or electroplating).

A highly conformal, continuous barrier layer is required to prevent copper diffusion into the adjacent semiconductor (i.e., silicon) material or dielectric. The barrier layer also often acts as an adhesion layer to promote adhesion between the dielectric and the copper seed layer. Low dielectric constant (i.e., low-k) dielectrics are typically used to reduce inter- and intra-line capacitance and cross-talk, but often suffer from poorer adhesion and lower thermal stability than traditional oxide dielectrics, making the choice of a suitable adhesion layer more critical. A non-conformal barrier layer, or one with poor step coverage or discontinuous step coverage, can lead to copper diffusion and current leakage between adjacent metal lines or to delamination at either the barrier-to-dielectric or barrier-to-seed layer interfaces, both of which adversely affect product lifetime and performance. The barrier layer should also be uniformly thin, to most accurately transfer the underlying trench and via sidewall profile to the subsequent seed layer, and have a low film resistivity (e.g., $\rho < 500 \mu\Omega\text{-cm}$) to lessen its impact on the overall conductance of the copper interconnect structures.

A highly conformal, uniformly thin, continuous seed layer with low defect density is required to prevent void formation in the copper wires. The seed layer carries the plating current and acts as a nucleation layer. Voids can form from discontinuities or other defects in the seed layer, or they can form from pinch-off due to gross overhang of the seed layer at the top of features, both trenches and vias. Voids adversely impact the resistance, electromigration, and reliability of the copper lines, which ultimately affects the product lifetime and performance.

Traditional thin film deposition techniques, for example, physical vapor deposition (PVD) and chemical vapor deposition (CVD), are increasingly unable to meet the requirements of advanced thin films. PVD, such as sputtering, has been used for depositing conductive thin films at low cost and at relatively low substrate temperature. Unfortunately, PVD is inherently a line of sight process, resulting in poor step coverage in high aspect ratio trenches and vias. Advances in PVD technology to address this issue have

resulted in high cost, complexity, and reliability issues. CVD processes can be tailored to provide conformal films with improved step coverage. Unfortunately, CVD processes often require high processing temperatures, result in the incorporation of high impurity concentrations, and have poor precursor (or reactant) utilization efficiency, leading to a high cost of ownership.

5 Atomic layer deposition (ALD), or atomic layer chemical vapor deposition (AL-CVD), is an alternative to traditional CVD methods to deposit very thin films. ALD has several advantages over PVD and traditional CVD. ALD can be performed at comparatively lower temperatures (which is compatible with the industry's trend toward lower temperatures), has high precursor utilization efficiency, can produce conformal thin film layers (i.e., 100% step coverage is theoretically possible), can control film thickness on
10 an atomic scale, and can be used to "nano-engineer" complex thin films.

A typical ALD process differs significantly from traditional CVD processes. In a typical CVD process, two or more reactant gases are mixed together in the deposition chamber where either they react in the gas phase and deposit on the substrate surface, or they react on the substrate surface directly. Deposition by CVD occurs for a specified length of time, based on the desired thickness of the deposited
15 film. Since this specified time is a function of the flux of reactants into the chamber, the required time may vary from chamber to chamber.

In a typical ALD process deposition cycle, each reactant gas is introduced sequentially into the chamber, so that no gas phase intermixing occurs. A monolayer of a first reactant is physisorbed or chemisorbed onto the substrate surface. Excess first reactant is pumped out, possibly with the aid of an inert purge gas.
20 A second reactant is introduced to the deposition chamber and reacts with the first reactant to form a monolayer of the desired thin film via a self-limiting surface reaction. The self-limiting reaction halts once the initially adsorbed first reactant fully reacts with the second reactant. Excess second reactant is pumped out, again possibly with the aid of an inert purge gas. A desired film thickness is obtained by repeating the deposition cycle as necessary. The film thickness can be controlled to atomic layer (i.e., angstrom scale)
25 accuracy by simply counting the number of deposition cycles.

Physisorbed precursors are only weakly attached to the substrate. Chemisorption results in a stronger, more desirable bond. Chemisorption occurs when adsorbed precursor molecules chemically react with active surface sites. Generally, chemisorption involves cleaving a weakly bonded ligand (a portion of the precursor) from the precursor, leaving an unsatisfied bond available for reaction with an active surface
30 site.

The substrate material can influence chemisorption. In current dual damascene copper interconnect structures, a barrier layer such as tantalum (Ta) or tantalum nitride (Ta₃N₅) must often simultaneously cover silicon dioxide (SiO₂), low-k dielectrics, nitride etch stops, and any underlying metals such as copper. Materials often exhibit different chemical behavior, especially oxides versus metals. In
35 addition, surface cleanliness is important for proper chemisorption, since impurities can occupy surface bonding sites. Incomplete chemisorption can lead to porous films, incomplete step coverage, poor adhesion between the deposited films and the underlying substrate, and low film density.

The ALD process temperature must be selected carefully so that the first reactant is sufficiently adsorbed (e.g., chemisorbed) on the substrate surface, and the deposition reaction occurs with adequate
40 growth rate and film purity. A temperature that is too high can result in desorption or decomposition (causing impurity incorporation) of the first reactant. A temperature that is too low may result in incomplete chemisorption of the first precursor, a slow or incomplete deposition reaction, no deposition

reaction, or poor film quality (e.g., high resistivity, low density, poor adhesion, and/or high impurity content).

Traditional ALD processes have several disadvantages. First, since the process is entirely thermal, selection of an appropriate process temperature is often confined to a narrow temperature window. Second, the small temperature window limits the selection of available precursors. Third, metal precursors that fit the temperature window are often halides (e.g., compounds that include chlorine, fluorine, or bromine), which are corrosive and can create reliability issues in metal interconnects. Fourth, either gaseous hydrogen (H_2) or elemental zinc (Zn) is often used as the second reactant to act as a reducing agent to bring a metal compound in the first reactant to the desired oxidation state of the final film. Unfortunately, H_2 is an inefficient reducing agent due to its chemical stability, and Zn has a low volatility and is generally incompatible with IC manufacturing. Thus, although conventional ALD reactors are suitable for elevated-temperature ALD, they limit the advancement of ALD processing technology.

Plasma-enhanced ALD, also called radical enhanced atomic layer deposition (REALD), was proposed to address the temperature limitations of traditional thermal ALD. For example, in U.S. Patent No. 5,916,365, the second reactant passes through a radio frequency (RF) glow discharge, or plasma, to dissociate the second reactant and to form reactive radical species to drive deposition reactions at lower process temperatures. More information on plasma-enhanced ALD is included in "Plasma-enhanced atomic layer deposition of Ta and Ti for interconnect diffusion barriers," by S. M. Rossnagel, et al., *Journal of Vacuum Science and Technology B* 18(4) July/August 2000 pp. 2016-2020.

Plasma enhanced ALD, however, still has several disadvantages. First, it remains a thermal process similar to traditional ALD since the substrate temperature provides the required activation energy, and therefore the primary control, for the deposition reaction. Second, although processing at lower temperatures is feasible, higher temperatures must still be used to generate reasonable growth rates for acceptable throughput. Such temperatures are still too high for some films of interest in IC manufacturing, particularly polymer-based low-k dielectrics that are stable up to temperatures of only 200°C or less. Third, metal precursors, particularly for tantalum (Ta), often still contain chlorine as well as oxygen impurities, which results in low density or porous films with poor barrier behavior and chemical instability. Fourth, the plasma enhanced ALD process, like the conventional sequential ALD process described above, is fundamentally slow since it includes at least two reactant gases and at least two purge or evacuation steps, which can take up to several minutes with conventional valve and chamber technology.

Conventional ALD reactors, including plasma enhanced ALD reactors, include a vertically-translatable pedestal to achieve a small process volume, which is important for ALD. A small volume is more easily and quickly evacuated (e.g., of excess reactants) than a large volume, enabling fast switching of process gases. Also, less precursor is needed for complete chemisorption during deposition. For example, the reactors of U.S. Patent No. 6,174,377 and European Patent No. 1,052,309 A2 feature a reduced process volume located above a larger substrate transfer volume. In practice, a typical transfer sequence includes transporting a substrate into the transfer volume and placing it on top of a moveable pedestal. The pedestal is then elevated vertically to form the bottom of the process volume and thereby move the substrate into the process volume. Thus, the moveable pedestal has at least a vertical translational and possibly a second rotational degree of freedom (for high temperature process uniformity).

Typical ALD reactors have significant disadvantages. First, conventional ALD reactors suffer from complex pedestal requirements, since the numerous facilities (e.g., heater power lines, temperature

monitor lines, and coolant channels) must be connected to and housed within a pedestal that moves.

Second, in the case of plasma enhanced ALD, the efficiency of radical delivery for deposition of conductive thin films is significantly decreased in downstream configurations in which the radical generating plasma is contained in a separate vessel remote from the main process chamber (see U.S. Patent No. 5,916,365).

5 Both gas phase and wall recombinations reduce the flux of useful radicals to the substrate. In the case of atomic hydrogen (H), recombination results in diatomic H₂, a far less effective reducing agent. Other disadvantages of known ALD reactors exist.

Accordingly, improved ALD reactors are desirable to make ALD better suited for commercial IC manufacturing. Desirable characteristics of such reactors might include higher throughput, improved
10 deposited film characteristics, better temperature control for narrow process temperature windows, and wider processing windows (e.g., in particular with respect to process temperature and reactant species).

SUMMARY

In accordance with one embodiment of the invention, a deposition system includes a process chamber, a stationary pedestal for supporting a substrate in the process chamber, and a moveable shield
15 forming at least a portion of an enclosure defining the process chamber. Motion of the shield with respect to the stationary pedestal controls a variable gas conductance path for gases flowing through the process chamber, thereby modulating the pressure of the process chamber with respect to an external volume. The moveable shield in accordance with an embodiment of the present invention may include several gas channel openings for introducing various process gases into the process chamber. In some embodiments,
20 the moveable shield may alternatively or additionally include an interior cooling or heating channel for temperature control.

The stationary pedestal in accordance with an embodiment of the present invention may include an electrostatic chuck (ESC) for improved coupling of RF power to the substrate, enabling improved ion generation, ion energy control, and uniform delivery of ions. Additionally, the use of an ESC in
25 conjunction with a suitable gas medium inserted in the region between the ESC and the substrate provides improved temperature control and uniformity.

The deposition system may be a portion of a reactor for atomic layer deposition (ALD) of barrier layers, adhesion layers, seed layers, low dielectric constant (low-k) films, high dielectric constant (high-k) films, and other thin films used in advanced integrated circuit fabrication technologies. The deposition
30 system may be used to deposit barrier layers, adhesion layers, seed layers, low dielectric constant (low-k) films, high dielectric constant (high-k) films, and other thin films used in advanced integrated circuit fabrication technologies.

A deposition system in accordance with an embodiment of the present invention provides several advantages. The system allows triggering of the deposition reaction by a non-thermal mechanism, leading
35 to higher quality films deposited at lower temperatures. The deposition process parameters, including pressure during processing, can be modulated quickly and more efficiently than is conventionally possible, leading to self-synchronization of the deposition and higher throughput. By coupling RF power to the stationary pedestal, the system allows improved ion generation, ion energy control, ion spatial uniformity, and uniform ion delivery for modulated, ion-induced deposition. The stationary pedestal/moveable shield
40 configuration simplifies the overall system design. Compared to conventional, heavy, moveable pedestals, a shield in one embodiment of the present invention can be quickly and precisely positioned by a linear

motor for improved performance. The system allows gas introduction through multiple points, possibly including through the shield, which increases the flexibility of deposition process design. In addition, a smaller total system volume is achievable with the stationary pedestal/moveable shield configuration.

5 In accordance with one embodiment of the invention, a deposition system includes a process chamber for conducting an ALD process to deposit layers on a substrate. An ESC retains the substrate. Various features of the ESC and various bias circuits are described. RF power is coupled to electrodes in the process chamber to generate ions and reactive atoms. In one embodiment, the RF power creates a plasma. Various RF generating circuits are described. Embodiments of the ALD processing system enable improved ion generation, improved ion energy control, and uniform delivery of ions to the substrate.

10 In accordance with one embodiment of the invention, a deposition system includes a backside gas that increases thermal coupling between the substrate and the ESC. The ESC is cooled via a coolant flowing through a coolant plate and is heated via a resistive heater.

In accordance with one embodiment of the invention, a process chamber containing a substrate has at least one process gas introduced for reacting with a surface of the substrate to form a layer on the
15 substrate. The gas creates a certain pressure in the chamber. At a certain time, the gas is expelled to end the reaction, and the gas pressure is reduced. The detection of the change in pressure in said chamber automatically controls valves to supply a second gas into the chamber to further react with the surface of the substrate.

In accordance with one embodiment of the invention, a deposition technique is an ALD process
20 based upon the sequential supply of at least two separate reactants into a process chamber. A first reactant reacts (becomes adsorbed) with the surface of the substrate via chemisorption. The first reactant gas is removed from the chamber, and a second reactant gas reacts with the adsorbed reactant to form a monolayer of the desired film. The process is repeated to form a layer of any thickness. To reduce the process time, there is no separate purge gas used to purge the first reactant gas from the chamber prior to
25 introducing the second gas, containing the second reactant. Instead, the purge gas also includes the second reactant. Thus, there can be very little or no delay between introducing the first and second gases. In one embodiment, a plasma of the second gas is created using an RF source, which forms energized ions and reactive atoms to drive the reaction at low temperatures. The process is self-limiting. By counting the cycles, the layer thickness is accurately controlled.

30 In accordance with one embodiment of the invention, electrodes in the electrostatic chuck assembly are biased so as to create a DC bias on the substrate to attract charged gas ions in the chamber to the substrate. Improved chemisorption results.

In accordance with one embodiment of the invention, multiple valves are arranged and controlled to selectively introduce process gases into the chamber.

35 In accordance with one embodiment of the invention, a deposition system includes a process chamber and one or more gas inlets. One gas inlet is formed as a ring surrounding the periphery of a substrate retained in the process chamber. Added control over a deposition process is obtained by such a ring. In one embodiment, the ring is moveable. Various arrangements of gas inlets and valves are described.

40 In accordance with one embodiment of the invention, instead of varying the gas flux on a substrate in the chamber by controlling the flow of gas upstream of the process chamber, the gas flux on the substrate is controlled by controlling the conductance between the process chamber and a lower pressure volume

outside the process chamber. The flux of the gas on the substrate varies inversely with the chamber conductance, such that the flux of the gas on the substrate increases when the conductance decreases. Various methods of performing an ALD process by controlling the conductance are disclosed as well as various structures for controlling the conductance.

5 These and other aspects and features of the disclosed embodiments will be better understood in view of the following detailed description of the exemplary embodiments and the drawings thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram of a novel ALD reactor.

Fig. 2 shows various embodiments of the shield and shadow ring overlap region of Fig. 1.

10 Fig. 3 is a schematic diagram showing top introduction of gas into the process chamber of the ALD reactor of Fig. 1.

Fig. 4 is (a) a schematic diagram and (b) a plan view schematic diagram showing side introduction of gas into the process chamber of the ALD reactor of Fig. 1.

15 Fig. 5 is (a) a schematic diagram and (b) a plan view schematic diagram showing both top and side introduction of gas into the process chamber of the ALD reactor of Fig. 1.

Fig. 6 is a schematic diagram of a control system for the pedestal of Fig. 1.

Fig. 7 is a schematic diagram of a circuit for electrical biasing of the electrostatic chuck of Fig. 1.

Fig. 8 is a front-side perspective view of a novel ALD reactor.

Fig. 9 is a back-side perspective view of the ALD reactor of Fig. 8.

20 Fig. 10 is a back-side perspective view, from below, of the ALD reactor of Fig. 8.

Fig. 11 is a front-side cutaway perspective view of the ALD reactor of Fig. 8.

Fig. 12 is a front-side cutaway perspective view of the ALD reactor of Fig. 8.

Fig. 13 is a cross-sectional view of a chamber portion of the ALD reactor along line 13-13 of Fig.

8.

25 Fig. 14 is a detailed cross-sectional view of the right side of the chamber portion of Fig. 13 showing a load shield position.

Fig. 15 is a detailed cross-sectional view of the right side of the chamber portion of Fig. 13 showing a low conductance process shield position.

30 Fig. 16 is a detailed cross-sectional view of the right side of the chamber portion of Fig. 13 showing a high conductance process shield position.

Fig. 17 is a detailed cross-sectional view of the right side of the chamber portion of Fig. 13 showing a purge shield position.

Fig. 18 is a schematic diagram of a valve system for gas delivery in the ALD reactor of Fig. 8.

Fig. 19 is a schematic diagram of a valve system for gas delivery in the ALD reactor of Fig. 8.

35 Fig. 20 is a schematic diagram of a valve system for gas delivery in the ALD reactor of Fig. 8.

Fig. 21 is a schematic diagram of a valve system for gas delivery in the ALD reactor of Fig. 8.

Fig. 22 is a schematic diagram of a valve system for gas delivery in the ALD reactor of Fig. 8.

Fig. 23 is a perspective cross-section of two embodiments of a showerhead for gas distribution.

40 Fig. 24 is a perspective cross-section of an embodiment of a shield assembly for the ALD reactor of Fig. 8.

Fig. 25 is a perspective cross-section of an embodiment of a shield assembly for the ALD reactor of Fig. 8.

Fig. 26 is a perspective cross-section of an embodiment of a shield assembly for the ALD reactor of Fig. 8.

5 Fig. 27 is a cutaway perspective view of an embodiment of an electrostatic chuck assembly for the ALD reactor of Fig. 8.

Fig. 28 is a schematic diagram of a control system for the electrostatic chuck assembly of Fig. 27 of the ALD reactor of Fig. 8.

10 Fig. 29 is a schematic diagram of a control system including an alternative energy source for the electrostatic chuck assembly of Fig. 27 of the ALD reactor of Fig. 8.

Fig. 30 is a perspective view of an embodiment of a portion of an electrostatic chuck assembly for the ALD reactor of Fig. 8.

Fig. 31 is a schematic diagram of a circuit for electrical biasing of the electrostatic chuck of the ALD reactor of Fig. 8.

15 Fig. 32 is a schematic diagram of a circuit for electrical biasing of the electrostatic chuck of the ALD reactor of Fig. 8.

Fig. 33 is a schematic diagram of a circuit for electrical biasing of the electrostatic chuck of the ALD reactor of Fig. 8.

20 Fig. 34 is a schematic illustration of a conventional ALD process.

Fig. 35 is a schematic illustration of a novel ALD process.

Fig. 36 shows timing diagrams for (a) a typical prior art ALD process and (b) a novel ALD process.

Fig. 37 shows timing diagrams for an alternative embodiment of a novel ALD process.

Fig. 38 shows timing diagrams for an alternative embodiment of a novel ALD process.

25 Fig. 39 is a schematic illustration of a novel chemisorption technique for ALD processes.

Fig. 40 is a schematic diagram of a circuit for electrical biasing of the electrostatic chuck of the ALD reactor of Fig. 8 for improved chemisorption.

In the drawings, like or similar features are typically labeled with the same reference numbers.

DETAILED DESCRIPTION OF EMBODIMENTS

30 Basic ALD Reactor Design

Fig. 1 is a schematic diagram of a novel ALD reactor 2. Reactor 2 includes a stationary pedestal 4, which may include an electrostatic chuck (ESC) 6 on top of which a substrate 8 rests. Substrate 8 is usually a semiconductor wafer (e.g., silicon), but may be a metallized glass substrate or other substrate. A chamber lid 10 and ESC 6 define the top and bottom boundaries, respectively, of a process chamber 12. The surrounding wall of chamber 12 is defined by a moveable shield 14, which is attached to a plurality of shield support legs 16. The volume of process chamber 12 is smaller than prior art batch reactors, but may be similar in size to prior art single wafer systems. The configuration of reactor 2, however, provides an overall volume of reactor 2 that can be smaller than that of prior art reactors, while providing the small volume of process chamber 12.

40 The small volume of process chamber 12 achieves the advantages of small process volumes discussed above, including quick evacuation, fast switching of process gases, and less precursor required

for complete chemisorption. The volume of process chamber 12 cannot be made arbitrarily small, however, since substrate 8 must still be transferred into, and out of, process chamber 12.

In Fig. 1, the fixed position of pedestal 4, including its supporting hardware, simplifies overall design of reactor 2, allowing ease of use and maintenance as well as improved performance. In comparison to massive moveable pedestals in prior art reactors, shield 14 includes less associated hardware and is much lighter, which allows precision positioning of shield 14 to adjust the conductance of, and facilitate pumping of, chamber 12 with rapid response.

A chamber body 18 surrounds shield 14, chamber lid 10, and pedestal 4 (including ESC 6), defining an annular pumping channel 20 exterior to shield 14. During processing, shield 14 separates process chamber 12, at low pressure, from annular pumping channel 20, which is maintained at a lower pressure than the chamber to maintain a clean background ambient in reactor 2. The volume of chamber 12 is coupled to annular pumping channel 20 via a shield conductance upper path 22 and a shield conductance lower path 24. Upper path 22 and lower path 24 are each defined by portions of shield 14 and corresponding features of stationary components of reactor 2. In the embodiment shown in Fig. 1, upper path 22, typically a variable low leakage path during processing, is bounded by an inner wall of shield 14 and chamber lid 10. Lower path 24, a variable high leakage path through a shield and shadow ring overlap region 26, is bounded by a portion of shield 14 and a shadow ring 28. Shadow ring 28 is actually separate from ESC 6 and is shown in greater detail in subsequent figures.

The structures of shield 14 and shadow ring 28 may vary to provide different conductances of lower path 24 as shown in Fig. 2, which shows various embodiments of the shield and shadow ring overlap region 26 of Fig. 1. The conductance of a flow path is related to the length of the restriction as well as the physical dimensions of the path. For example, a shorter path with a large cross-sectional area has a higher conductance. For the embodiments shown in Fig. 2, the structural configurations of shield 14 and shadow ring 28 result in a highest conductance path 30, a second highest conductance path 32, a third highest conductance path 34, and a lowest conductance path 36. Practitioners in the art will appreciate that many other embodiments of shield and shadow ring overlap region 26 are possible.

Various shield positions are employed throughout a novel ALD process. Raising shield 14 to its highest position (along with shadow ring 28) allows for introduction or removal of substrate 8. Dropping shield 14 to its lowest position allows rapid evacuation of chamber 12 via upper path 22 by exposure to the vacuum of annular pumping region 20. Shield 14 is positioned at intermediate positions during processing depending on gas delivery and conductance requirements.

The motion of shield 14 can be used to precisely control the spatial relationship between shield 14 and shadow ring 28, thereby providing a tunable conductance for chamber 12 primarily via lower path 24. This allows quick, precise control of the pressure in chamber 12, even during processing, which is not possible in prior art methods that employ a moveable pedestal since vertical motion of substrate 8 is undesirable during processing. The tunable conductance also allows quick, precise control of the residence time of gases introduced to chamber 12 for multiple flow rates, and it allows minimal waste of process gases.

Basic Gas Introduction to an ALD Reactor

Reactor 2 of Fig. 1 supports gas introduction through multiple points, including top introduction, side introduction, or a combination of both top and side introductions.

Fig. 3 is a schematic diagram showing top introduction of gas into process chamber 12 of ALD reactor 2 of Fig. 1. A top mount feed (not shown) has a single introduction point (or multiple introduction points) with an optional added device (not shown), such as a showerhead and/or a baffle, to ensure that a top introduction flow distribution 38 is uniform over the substrate. The added device includes at least one passage, and may include many. The added device may also include intermediate passages to regulate gas distribution and velocity.

Fig. 4 is (a) a schematic diagram and (b) a plan view schematic diagram showing side introduction of gas into process chamber 12 of ALD reactor 2 of Fig. 1. Gas is introduced from a gas channel 40 in shield 14 into process chamber 12 through orifices in an inner wall of shield 14. Gas is introduced in a symmetric geometry around substrate 8 designed to ensure that a side introduction flow distribution 42 is even. In addition, the plane of the gas introduction may be adjusted vertically relative to substrate 8 before or during gas introduction, which can be used to optimize flow distribution 42.

Fig. 5 is (a) a schematic diagram and (b) a plan view schematic diagram showing both top and side introduction of gas into process chamber 12 of ALD reactor 2 of Fig. 1. The gases for novel ALD processes, including precursor and purge gases, can be introduced through the same introduction path or separate paths as desired for optimal performance and layer quality.

Basic Electrostatic Chuck Assembly Design for an ALD Reactor

Reactor 2 of Fig. 1 can be used in a deposition process where the activation energy for the surface reaction is provided by ions created in a plasma above the substrate. Thus, atomic layer deposition can be ion-induced, rather than thermally induced. This allows deposition at much lower temperatures than conventional ALD systems. Given the sufficiently low process temperatures, pedestal 4 may include an electrostatic chuck (ESC) 6 for improved temperature control and improved radio frequency (RF) power coupling.

Additional detail of ion-induced atomic layer deposition may be found in the following related applications. U.S. Application Serial No. 09/812,352, entitled "System And Method For Modulated Ion-Induced Atomic Layer Deposition (MII-ALD)," filed March 19, 2001, assigned to the present assignee and incorporated herein by reference. U.S. Application Serial No. 09/812,486, entitled "Continuous Method For Depositing A Film By Modulated Ion-Induced Atomic Layer Deposition (MII-ALD)," filed March 19, 2001, assigned to the present assignee and incorporated herein by reference. U.S. Application Serial No. 09/812,285, entitled "Sequential Method For Depositing A Film By Modulated Ion-Induced Atomic Layer Deposition (MII-ALD)," filed March 19, 2001, assigned to the present assignee and incorporated herein by reference.

Fig. 6 is a schematic diagram of a control system 44 for pedestal 4 of Fig. 1. Substrate 8 rests on an annular sealing lip 46 defining a backside gas volume 48 between substrate 8 and a top surface 50 of ESC 6 of pedestal 4. The backside gas flows from a backside gas source 52 along a backside gas line 54, through a backside gas passageway 56 in ESC 6, and into gas volume 48. The backside gas improves the thermal communication between substrate 8 and ESC 6 by providing a medium for thermal energy transfer between substrate 8 and ESC 6. A means of flow control, such as a pressure controller 58, maintains the backside gas at a constant pressure, thus ensuring a uniform substrate temperature.

Substrate temperature is modulated by heating or cooling ESC 6. A temperature sensor 60 is coupled via a sensor connection 62 to a temperature monitor 64. A temperature controller 66 controls a

heater power supply 68 applied via an electrical connection 70 to a resistive heater 72 embedded in ESC 6. A coolant temperature and flow controller 74, as is widely known, controls the coolant from a coolant supply 76 as it flows in a plurality of coolant channels 78 in pedestal 4.

ESC 6 includes at least a first electrode 80 and a second electrode 82 embedded in a dielectric material. Fig. 7 is a schematic diagram of a circuit 84 for electrical biasing of electrostatic chuck 6 of pedestal 4 of Fig. 1. First electrode 80 and second electrode 82 are biased with different DC potentials to provide the "chucking" action that holds substrate 8 (Fig. 1) to ESC 6 prior to plasma ignition and during deposition. The biasing scheme of Fig. 7 allows establishment of the electrostatic attraction (i.e., "chucking") at low biases that would be insufficient to generate enough electrostatic attraction with a conventional monopolar chuck. In Fig. 7, one terminal of a DC power supply 86 is coupled via a first inductor 88 to first electrode 80. The other terminal of DC power supply 86 is coupled via a second inductor 90 to second electrode 82. Inductors 88 and 90 serve as RF filters.

RF power (e.g., at 13.56 MHz) is also supplied simultaneously to both first electrode 80 and second electrode 82 using an RF generator 92 coupled to a ground terminal 94. A first capacitor 96 and a second capacitor 98 are respectively coupled between RF generator 92 and first electrode 80 and second electrode 82. Capacitors 96 and 98 serve as DC filters to block the DC voltage from power supply 86. Circuit 84 allows improved coupling of RF power to substrate 8 during processing due to the close proximity (e.g., 0.6 mm–2 mm spacing) of substrate 8 to first electrode 80 and second electrode 82 embedded in ESC 6.

Since substrate 8 is in such close proximity to first and second electrodes 80 and 82, the transmission efficiency of RF power through the intervening dielectric of ESC 6 is higher than in conventional reactors where RF power is applied to electrodes at a greater distance from the substrate. Thus, less power is needed to achieve sufficient RF power coupling to substrate 8 in novel ALD reactor 2 (Fig. 1), and the same power to generate the bias on substrate 8 can also be used to create a plasma above substrate 8 at very low powers (e.g., < 600 W, and typically < 150 W).

ALD Reactor Detail

Fig. 8, Fig. 9, Fig. 10, Fig. 11, and Fig. 12 show external views and internal cutaway views of a novel ALD reactor 100. Fig. 8 is a front-side perspective view of reactor 100. Fig. 9 is a back-side perspective view of reactor 100. Fig. 10 is a back-side perspective view, from below, of reactor 100. Fig. 11 is a front-side cutaway perspective view of reactor 100. Fig. 12 is another front-side cutaway perspective view of reactor 100.

Referring to Fig. 8, a substrate 8 (Fig. 12) is transferred into or out of a process chamber 12 (Fig. 11 and Fig. 12) of reactor 100 through a substrate entry slot 102 in a slit valve 104. Substrate 8 is loaded onto or unloaded from the pedestal (e.g., an electrostatic chuck assembly 106 as seen in Fig. 11 and Fig. 12) by a plurality of lift pins 108. In the load or unload position, the tips of lift pins 108 extend through orifices in an electrostatic chuck (ESC) 6 to hold substrate 8 above the top surface of ESC 6. In the process position, the tips of lift pins 108 retract below the top surface of ESC 6 allowing contact between substrate 8 and ESC 6 (Fig. 11 and Fig. 12).

Referring to Fig. 11 and Fig. 12, lift pins 108 extend downward from process chamber 12 in the interior of reactor 100 through an electrostatic chuck assembly 106 (including ESC 6, a cooling plate 110, and a baseplate 112) to the exterior under-side of reactor 100. Each of lift pins 108 is attached to a lift pin

spider 114 to coordinate their motion. Vertical translation of lift pin spider 114 is accomplished with an off-axis lift pin actuator 116 (e.g., a pneumatic cylinder), which controls motion of a tie rod 118 that is coupled to lift pin spider 114 by a spherical joint 120 as seen in Fig. 10. Spherical joint 120 transmits lifting forces to lift pin spider 114 but no moments.

5 Referring to Fig. 11, to facilitate substrate transfer, a moveable shield 14, must be in a load position. Shield 14 is raised or lowered using a linear motor 122, which moves a linear motor output rod 124 attached to a shield lift spider 126 by a collet clamp 128 (best seen in Fig. 10). Each one of a plurality of shield support legs 16 (Fig. 11) extends through a shield support leg seal 130 and is coupled between shield lift spider 126 and shield 14. The axis of linear motor 122 is aligned with the axis of process
10 chamber 12 resulting in no net moments on shield lift spider 126. Lift pin spider 114 rides a portion of linear motor output rod 124, coaxial with output rod 124 and shield lift spider 126. Lift pin spider 114, however, is unaffected by movement of rod 124, and this arrangement results in no net moments on lift pins 108.

As mentioned above, linear motor 122 provides actuation of shield 14. This is in contrast to
15 conventional moveable pedestals wherein slower stepper motors are used for actuation. Conventional rotational stepper motors use lead screws (possibly in conjunction with a gear train), which are slow but capable of moving heavy masses, to effect movement of the heavy pedestal. Linear motor 122 does not use a gear train, but instead directly drives the load. Linear motor 122 includes a plurality of alternating magnets to effect motion of output rod 124.

20 Linear motor 122 can be a commercially available linear motor and typically includes a sleeve having a coil and a moveable rod enclosing the series of alternating magnets. The movement of the rod through the sleeve is precisely controlled, using a Hall Effect magnetic sensor, by a signal applied to the coil. In one embodiment, pulses applied to the coil precisely control the position of the rod with respect to the sleeve, as is well known. Since shield 14 is a light weight compared to conventional heavy pedestals,
25 linear motor 122 provides high performance positioning, with response times on the order of milliseconds. Linear motor 122 thus provides a quicker response and more accurate shield positioning than is achievable with conventional stepper or servo motors used to actuate the pedestal of conventional ALD reactors.

Referring to Fig. 11, a pump, such as a turbomolecular pump 132, maintains a background ambient pressure as low as a few microtorr or less in an annular pumping channel 20 surrounding shield 14.
30 Pump 132 is attached to reactor 100 at an angle such that a circular pump throat 134 is fully exposed to a narrow pumping slot 136 aft of process chamber 12, maximizing the conductance between them. In this manner, pump 132 with a diameter, d , has maximum exposure to pumping slot 136 of height, h (where $h < d$), with minimum restriction between pump 132 and chamber 12 (see also Fig. 13 discussed below). For specific processing applications, a pumping speed restrictor 138 can be inserted at pump throat 134 to
35 restrict the conductance as needed. In some embodiments, a pressure controlling throttle valve (e.g., a butterfly valve) can be used instead of, or in conjunction with, restrictor 138. Pressure in pumping slot 136 and annular pumping channel 20 is monitored by a pump pressure sensor 140 mounted on the top surface of reactor 100.

Process chamber 12 is bounded on top by a chamber lid 10. Pressure in process chamber 12 of
40 reactor 100 may be on the order of a few microtorr up to several torr. The pressure of chamber 12 is monitored by a fast chamber pressure sensor 142 and a precision chamber pressure sensor 144, both of which are mounted on an upper peripheral flange of chamber lid 10 (Fig. 8). The temperature of chamber

lid 10 is controlled by fluid flowing in a plurality of lid cooling/heating channels 146 (Fig. 11). One possible path of gas introduction to process chamber 12 is through a showerhead three-way valve 148 mounted centrally on chamber lid 10. Another possible method of gas introduction to process chamber 12 is through a shield gas channel 40.

5 RF power is transferred to electrodes in ESC 6 via an RF conductor 150 shielded within an RF insulator tube 152. A gas medium (commonly referred to as a backside gas) is provided via a backside gas valve 154 to ESC 6 to improve the thermal coupling between ESC 6 and substrate 8. During processing, an optional shadow ring 28 rests on a portion of ESC 6 fully surrounding a peripheral edge of substrate 8.

10 Fig. 13 is a cross-sectional view of a chamber portion 156 of ALD reactor 100 along line 13-13 of Fig. 8. Substrate entry slot 102 is shown on the left hand side extending through a chamber body 18. Pumping slot 136, of height h , is shown on the right hand side extending through chamber body 18 to pump throat 134, of diameter d . The temperature of chamber body 18 is controlled by fluid flowing in a chamber cooling/heating channel 158.

15 Chamber lid 10 rests atop chamber body 18. A vacuum seal, to maintain low pressure in the interior of reactor 100, is maintained through the use of an upper O-ring 160 between chamber lid 10 and chamber body 18. Laterally spaced from O-ring 160 between chamber lid 10 and chamber body 18 is an upper RF gasket 162, forming an RF shield. The temperature of chamber lid 10 is controlled by fluid flowing in lid cooling/heating channels 146. Alternatively, the temperature of chamber lid 10 may be controlled by an electric or resistive heater or other cooling/heating means.

20 The pressure in process chamber 12 is monitored, in part, by fast chamber pressure sensor 142, which is mounted on an upper peripheral flange of chamber lid 10. Pressure sensor 142 monitors the pressure in a pressure tap volume 164, which is coupled to process chamber 12 by a pressure sensor orifice 166. This arrangement allows exposure of pressure sensor 142 to the pressure of chamber 12, while preventing plasma and other process chemistries from reaching, and possibly damaging, pressure sensor 142.

25 Gases can be introduced into process chamber 12 through a showerhead gas feed inlet 168, which leads to a plenum 170 above a showerhead 172 attached to a lower surface of chamber lid 10. Showerhead 172 includes a showerhead lip 174 and a plurality of showerhead gas orifices 176, which are used to distribute gas evenly into process chamber 12.

30 Substrate 8 rests on an upper surface of an ESC assembly 106, which includes in part, ESC 6, cooling plate 110, and baseplate 112. The vertical spacing between the upper surface of ESC assembly 106 and showerhead 172 may be 0.3 inches to 1 inch, typically less than 0.6 inches. Backside gas passageway 56 is shown centrally located in and extending through ESC 6. ESC 6, which includes the largest portion of the upper surface on which substrate 8 rests, is held in contact with cooling plate 110 using a clamp ring 178, which overlaps a surrounding flange at the base of ESC 6. A plurality of clamp ring fasteners 180, each extending through clamp ring 178 into cooling plate 110, secure the connection between ESC 6 and cooling plate 110. A process kit 182 fully surrounds clamp ring 178 and electrically hides clamp ring fasteners 180 from ESC 6 and substrate 8. For a more detailed view of clamp ring 178, fasteners 180, and process kit 182, see Fig. 16, discussed below.

40 The temperature of cooling plate 110 is controlled using fluid flowing in a plurality of coolant channels 78 as shown in Fig. 13. An upper surface of cooling plate 110 is patterned to create a plurality of thermal breaks 184, or gaps, between ESC 6 and cooling plate 110. Thermal breaks 184 increase the

temperature difference between ESC 6 and cooling plate 110. This allows the temperature of ESC 6 to rise substantially higher than the temperature of baseplate 112, which stays relatively cool. For a more detailed view of thermal breaks 184, see Fig. 27, discussed below.

As shown in Fig. 13, a lower surface of cooling plate 110 is attached to an upper surface of baseplate 112. The upper surface of baseplate 112 forms the lower walls of coolant channels 78 in cooling plate 110. A vacuum seal, to maintain low pressure in the interior of reactor 100, is maintained through the use of an O-ring 186 between baseplate 112 and chamber body 18. Laterally spaced from O-ring 186 between baseplate 112 and chamber body 18 is an RF gasket 188.

One of the plurality of lift pins 108 is shown in retracted process position, with the tip of lift pin 108 below the top surface of ESC 6. Lift pin 108 extends through a lift pin seal 190, which maintains the low pressure in the interior of reactor 100. A lift pin bushing 192 reduces friction during vertical translation of lift pin 108 through aligned orifices in baseplate 112, cooling plate 110, and ESC 6.

In Fig. 13, shield 14 is shown in an intermediate process position. Process chamber 12 is thus bounded on the top by showerhead 172, on the bottom largely by ESC 6, and on the sides by shield 14 to confine a plasma 194. Shield 14 includes shield gas channel 40 and is attached to each shield support leg 16 using a shield cap 196. Each shield support leg 16 extends through shield support leg seal 130, which maintains the low pressure in the interior of reactor 100. A plurality of shield support leg bushings 198 reduce friction during vertical translation of shield support legs 16 through orifices in baseplate 112.

A shadow ring hook 200 is attached to a lower portion of shield cap 196. Shadow ring hook 200 is shown interdigitated with shadow ring 28, which fully surrounds a peripheral edge of ESC assembly 106 and rests on a process kit bevel 202 of process kit 182. Shadow ring 28 protects the underlying portions of ESC assembly 106 during deposition onto substrate 8. Shadow ring 28 also defines the circumferential region near the edge of substrate 8 where deposition is masked. Shadow ring 28 also plays a role in defining the chamber conductance. For a more detailed view of process kit bevel 202, see Fig. 16, discussed below.

In Fig. 13, two leakage paths modulate gas flow between process chamber 12 and annular pumping channel 20, which is largely bounded by chamber body 18, chamber lid 10, and ESC assembly 106. The leakage occurs due to differing pressures between process chamber 12 and annular pumping channel 20. A shield conductance upper path 22 is bounded on one side by an inner upper surface of shield 14, and on the other side by outer surfaces of chamber lid 10 and showerhead 172. A shield conductance lower path 24 is bounded on one side by surfaces of a lower portion of shield 14, shield cap 196, and shadow ring hook 200, and on the other side by surfaces of shadow ring 28. Upper path 22 leads from process chamber 12 to an upper portion 204 of annular pumping channel 20, while lower path 24 leads from process chamber 12 to a lower portion 206 of annular pumping channel 20.

Shield 14 can be vertically translated by either raising it into upper portion 204 of annular pumping channel 20 or lowering it into lower portion 206 of annular pumping channel 20. As shield 14 is translated, the conductances of upper path 22 and lower path 24 are changed. The variations in conductance can be controlled to vary the pressure in process chamber 12 in a controlled manner as needed for various steps in an atomic layer deposition process sequence.

Shield Operation

Unlike in conventional ALD reactors, reactor 2 includes a stationary pedestal 4 (see Fig. 1). For example, reactor 100 of Fig. 12 includes ESC assembly 106. Transfer of substrate 8 into process chamber

12 of reactor 100 is facilitated through the use of moveable shield 14, which also plays a significant role during processing.

Various shield positions are employed throughout the ALD process. Fig. 14, Fig. 15, Fig. 16, and Fig. 17 show detailed cross-sectional views of the right side of chamber portion 156 of Fig. 13, showing shield 14 in a substrate load shield position 208 (Fig. 14), a low conductance process shield position 210 (Fig. 15), a high conductance process shield position 212 (Fig. 16), and a purge shield position 214 (Fig. 17).

In load shield position 208 of Fig. 14, shield support legs 16 are raised by linear motor 122 (Fig. 8). When shield 14 is raised above a certain point, shadow ring hook 200 contacts shadow ring 28 and lifts it as well. Shield 14 and shadow ring 28 are then raised together. Shield 14 enters upper portion 204 of annular pumping channel 20. Shield 14 and shadow ring 28 can be raised until shadow ring 28 contacts showerhead lip 174, which prevents shadow ring 28 from contacting showerhead 172.

Load shield position 208 thus allows loading (or unloading) of substrate 8 into (or out of) process chamber 12 via substrate entry slot 102 (Fig. 13). For example, to load substrate 8 into process chamber 12, a substrate blade or paddle (not shown) carries substrate 8 into process chamber 12. Lift pins 108 are raised by lift pin actuator 116 (Fig. 10) to contact substrate 8 and lift it off the top surface of the blade. The blade is then retracted out of chamber 12 through entry slot 102. Lift pins 108 are retracted past the top surface of ESC 6 allowing substrate 8 to rest on ESC 6 as shown in Fig. 14. A similar process is followed to unload substrate 8 from chamber 12.

In an alternative embodiment, shadow ring 28 is not used, and shield 14 forms variable conduction paths with other surfaces that may be fixed or moveable. In some embodiments, it is possible that the load position may be achieved by lowering shield 14 sufficiently so that substrate 8 may pass over the top edge of shield 14.

Once substrate 8 has been loaded into process chamber 12, shield 14 is lowered by linear motor 122 (Fig. 8) for processing. The low conductance process shield position 210 shown in Fig. 15, shows the positions of shield 14 and shadow ring 28 at the moment that shadow ring 28 contacts process kit 182. An angled shadow ring seat 216 of shadow ring 28 rests on process kit bevel 202 of process kit 182. This is the only point of contact between shadow ring 28 and process kit 182. Air gaps separate shadow ring 28 and process kit 182 away from each edge of process kit bevel 202. The airgaps between shadow ring 28 and process kit 182 allow for differential thermal expansion of shadow ring 28 and process kit 182 during processing. The angle of process kit bevel 202 helps center shadow ring 28, through interaction with the angle of shadow ring seat 216, so that the edge of substrate 8 is shadowed uniformly by a shadow ring edge 218 of shadow ring 28.

Lowering shield 14 into process position creates shield conductance upper path 22 and shield conductance lower path 24, as described with respect to Fig. 13 above. While it is possible to reduce the conductance of lower path 24 to zero (Fig. 15), during deposition upper path 22 generally forms a low conductance leakage path, while lower path 24 generally forms a higher conductance leakage path (Fig. 16).

By changing the relative position of shield 14 to shadow ring 28, the conductance out of chamber 12 can be modulated. This modulation, in turn, alters the pressure of chamber 12. The high conductance process shield position 212 shown in Fig. 16, shows the positions of shield 14 and shadow ring 28 at an intermediate step of an ALD process. Lower path 24 includes several distinct regions: a plurality (three in

this embodiment) of fixed conductance regions 220 (fixed gaps between shadow ring hook 200 and shadow ring 28) interspersed with a plurality (two in this embodiment) of variable conductance regions 222 (variable gaps). The volumes of fixed conductance regions 220 and variable conductance regions 222 can be precisely controlled (by precise positioning of shield 14 by linear motor 122) to adjust the conductance of lower path 24, and therefore the pressure of chamber 12, as needed during the process.

In purge shield position 214 of Fig. 17, shield support legs 16 are lowered by linear motor 122 (Fig. 8). Shield 14 and shadow ring hook 200 are lowered into lower portion 206 of annular pumping channel 20. Shadow ring 28 remains seated on process kit 182. Both shield conductance upper path 22 and shield conductance lower path 24 become high conductance paths. Purge shield position 214 allows quick evacuation of the gases in process chamber 12 into annular pumping channel 20 due to the high conductances created and the lower pressure of annular pumping channel 20 compared to chamber 12.

As mentioned above, linear motor 122 (Fig. 8) provides actuation of shield 14. This allows quick and accurate variation of the conductance of shield conductance upper and lower paths 22 and 24. This translates into quick and accurate variation of the pressure in process chamber 12 for given gas flows into process chamber 12.

In some embodiments, a throttle valve (i.e., a butterfly valve, a variable position gate valve, a pendulum valve, etc.) positioned at pump throat 134 (Fig. 13) can also be used in conjunction with moveable shield 14 to effect quick pressure changes in process chamber 12 by modulating the maximum pumping speed of pump 132 (Fig. 12). The throttle valve augments the pressure range achievable in process chamber 12, providing a "coarse adjustment" of the pressure in process chamber 12, while shield 14 provides a "fine adjustment" of the pressure.

Showerhead and Shield Design for Gas Introduction and Temperature Control

The novel hardware for ALD reactor 100 (Fig. 11) supports the introduction of gases into process chamber 12 through multiple points. The primary introduction point is through the top of reactor 100, in particular, through showerhead three-way valve 148 (mounted on chamber lid 10) and showerhead 172 (best seen in Fig. 13). Gases may also be introduced into chamber 12 through shield 14, which may be additionally configured for temperature control.

Fig. 18 is a schematic diagram of a novel valve system 224 for gas delivery in ALD reactor 100 of Fig. 8. This embodiment delivers a single precursor and a purge gas to process chamber 12, either separately or in a mixed proportion. The purge gas is used to purge the chamber and as the gas source to strike a plasma. A carrier gas for the precursor flows from a first gas source 226, and the purge gas flows from a second gas source 228.

When either the carrier gas or the purge gas is not flowing to chamber 12, it is diverted by a first three-way valve 230 and a purge three-way valve 232, respectively, through a pump bypass gas line 234 to a vacuum pump 236. Utilization of vacuum pump 236 allows the carrier and purge gases to flow in steady state conditions even when they are not flowing to chamber 12. This avoids disturbances in the gas flows caused by the long settling times of gas sources that are switched on and off.

A showerhead three-way valve 148 controls access to a chamber gas line 238, which leads to process chamber 12. Three-way valve 148, located centrally on chamber lid 10 as seen in Fig. 11, provides at least two distinct advantages. First, gases introduced to chamber 12 can be switched rapidly with

minimal loss or delay. Second, gases are isolated from each other outside of chamber 12, resulting in no cross-contamination of reactants.

A first on/off valve 240 is coupled between first ends of a second on/off valve 242 and a third on/off valve 244. The opposite ends of second and third on/off valves 242 and 244 are each coupled to a first precursor source 246. First on/off valve 240 is also coupled between first three-way valve 230 and showerhead three-way valve 148 via a gas line 248 and a gas line 250, respectively. Precursor source 246 can be isolated by closing on/off valves 242 and 244. This may be done, for example, to change precursor source 246. In this case, on/off valve 240 may be closed, or opened to allow carrier gas to flow through three-way valves 230 and 148 into chamber 12. During deposition, first on/off valve 240 is normally closed, and second and third on/off valves 242 and 244 are normally open.

Three-way valves 230, 232, and 148 are switched synchronously to deliver either precursor or purge gas to chamber 12. When delivering precursor, purge three-way valve 232 is switched to flow the purge gas to vacuum pump 236, and showerhead three-way valve 148 is switched to the precursor side. Simultaneously, three-way valve 230 is switched to allow carrier gas to flow from first gas source 226 through gas line 248 and on/off valve 242 into precursor source 246. The carrier gas picks up precursor in precursor source 246, typically by bubbling through a liquid source. The carrier gas, now including precursor, flows through on/off valve 244, through gas line 250, through showerhead three-way valve 148, through chamber gas line 238, and into chamber 12.

When delivering purge gas, first three-way valve 230 is switched to flow the carrier gas to vacuum pump 236. Purge three-way valve 232 and showerhead three-way valve 148 are switched to allow purge gas to flow from second gas source 228 through a gas line 252 and chamber gas line 238 into chamber 12.

Valve system 224 keeps gas line 248 charged with carrier gas, gas line 250 charged with carrier plus precursor, and gas line 252 charged with purge gas. This allows fast switching between gas sources by significantly reducing the gas delivery time to chamber 12. Valve system 224 also minimizes waste of gases since gas lines do not need to be flushed between deposition steps. Furthermore, any gas bursts from transient pressure spikes upon gas switching, due to the charged gas lines, would only help the initial stages of chemisorption or surface reaction.

Practitioners will appreciate that alternative embodiments of valve systems for gas delivery to reactor 100 are possible. In the embodiment shown in Fig. 18, two separate gas sources are shown providing the carrier gas and the purge gas, which may be different gases. It is possible, however, that in some embodiments the same gas used as the purge gas may be used as the carrier gas for the precursor. In this case, separate gas sources may be used as shown in Fig. 18, or first gas source 226 may be used singly in a valve system 254, which has many similar components to valve system 224 of Fig. 18, as shown schematically in Fig. 19. Valve system 254 can be simplified by replacing three-way valve 230 with a T-junction 256 as shown schematically in Fig. 20 for a valve system 258, which has many similar components to valve system 224 of Fig. 18. As in valve system 224 of Fig. 18, showerhead three-way valves 148 in valve system 254 (Fig. 19) and valve system 258 (Fig. 20) control the flow of purge gas or carrier-plus-precursor gas to chamber 12. As shown in valve system 254 (Fig. 19) and valve system 258 (Fig. 20), pump 236 may not be used in some embodiments.

In some embodiments, gas delivery of multiple precursors may be desirable. Two embodiments of multiple precursor delivery are shown in the schematic diagrams of a valve system 260 in Fig. 21 and a valve system 262 in Fig. 22. Valve systems 260 (Fig. 21) and 262 (Fig. 22) each have many similar

components to valve system 224 of Fig. 18. Valve systems 260 (Fig. 21) and 262 (Fig. 22) are shown configured for two precursor sources, but may be further adapted for additional precursor sources. In each of valve systems 260 (Fig. 21) and 262 (Fig. 22), a second three-way valve 264 controls the flow of carrier gas to a second precursor source 266. A fourth on/off valve 268, a fifth on/off valve 270, and a sixth on/off valve 272 are coupled similarly to, and operate similarly to, valves 240, 242, and 244, respectively, to control the flow of carrier gas through second precursor source 266. A gas line 274, similar to gas line 248, is coupled between three-way valve 264 and on/off valve 270.

In Fig. 21, valve system 260 further includes a third gas source 276 in addition to first and second gas sources 226 and 228 of valve system 224 of Fig. 18. A third three-way valve 278, coupled to on/off valve 272 via a gas line 280, controls delivery of the second precursor to showerhead three-way valve 148 via a gas line 282. A fourth three-way valve 284 controls delivery of the purge gas via gas line 252 and a gas line 286 to three-way valve 278, which directs the purge gas to showerhead three-way valve 148 as needed via gas line 282.

In Fig. 22, valve system 262 is shown configured to use gas source 226 for both the purge and carrier gases. The carrier gas is delivered from gas source 226 to three-way valve 264 via a gas line 288. The purge gas is delivered to the second terminal of a third three-way valve 278 (and similar valves of any additional precursor sources) via gas line 252. The third terminal of three-way valve 278 is coupled to the second terminal of showerhead three-way valve 148 via gas line 282. Three-way valve 278 thus controls delivery of the second precursor and the purge gas to showerhead three-way valve 148.

Other modifications may be made for alternative embodiments of the valve systems of Figs. 18, 19, 20, 21, and 22. The functions of showerhead three-way valve 148 may be accomplished instead with an equivalent network of on/off valves (similar to valves 240, 242, and 244) and fittings. Metering valves may be added to branches to regulate the flow for specific branches. Pressure sensors may be added to branches and coupled with the valve actuation to introduce known amounts of reactant. Valve timing may be manipulated to deliver "charged" volumes of gas to process chamber 12. The traditional valves may be replaced with advanced designs such as micro-electromechanical (MEM) based valves or valve networks. The entire valve system can be heated to prevent condensation of reactants in the network.

Fig. 23 is a perspective cross-section of two embodiments of a showerhead 172 for gas distribution. Showerhead 172 is designed to have a larger diameter, and thus a larger area, than substrate 8 and ESC 6 (Fig. 13). Showerhead 172 includes a plurality of mounting holes 290 used to facilitate attachment of showerhead 172 to chamber lid 10 with a plurality of fasteners (see Fig. 13). Showerhead 172 also includes a plurality of pressure sensor orifices 166, one for each pressure sensor used to sense the pressure in process chamber 12. For example, fast chamber pressure sensor 142 and precision chamber pressure sensor 144 (Fig. 8) would each require a pressure sensor orifice 166 in showerhead 172. Showerhead 172 also includes showerhead lip 174 peripherally around the edge of showerhead 172 used to prevent shadow ring 28 from hitting showerhead 172.

Showerhead 172 also includes a cavity 292 centrally located in an upper surface of showerhead 172 as shown in Fig. 23 (a). Cavity 292 forms plenum 170 (Fig. 13) upon attachment of showerhead 172 to chamber lid 10. A plurality of showerhead gas orifices 176 are arranged within cavity 292 in a pattern designed for a particular gas flow distribution. The diameter of cavity 292 is designed to be larger than the diameter of substrate 8 (Fig. 13). In the embodiment of Fig. 23 (b), showerhead 172 includes a cavity 294 that is similar to cavity 292 of Fig. 23 (a), but cavity 294 has a diameter designed to be smaller than the

diameter of substrate 8. Practitioners will appreciate that a number of different diffusing devices may be used to tailor the directionality of the gas flows as needed.

As mentioned above, gas may also be introduced into process chamber 12 through shield 14. This allows cylindrical gas introduction around the volume of process chamber 12 as discussed above with reference to Fig. 4. Fig. 24 is a perspective cross-section of an embodiment of a shield assembly 296, including a shield gas channel 40, for ALD reactor 100 of Fig. 8. A plurality of shield support legs 16 attach to shield cap 196, which is attached to the base of shield 14. Most of shield support legs 16 are solid. Gas is introduced into shield 14, through at least one hollow shield support leg 298, which extends through shield cap 196 into shield gas channel 40 in shield 14.

Shield gas channel 40 is annular and runs completely around the base of shield 14. Shield gas channel 40 is a high conductance channel that allows introduced gas to distribute evenly around shield gas channel 40 of shield 14 before introduction into process chamber 12 (Fig. 13). Gas is introduced to chamber 12 through a plurality of gas flow orifices 300, which are evenly spaced along shield gas channel 40 and extend through an inner wall of shield 14 into process chamber 12. The gas introduction path of shield assembly 296 is designed to ensure uniform gas flow around substrate 8 as discussed with reference to Fig. 4.

Introduction of gas through shield 14 allows tremendous flexibility in designing ALD processes. In some embodiments, the same gas introduced through showerhead 172 can be simultaneously introduced through shield 14 to provide improved coverage in process chamber 12 and on substrate 8 (Fig. 13).

Alternatively, in some embodiments, one gas can be introduced through showerhead 172 while a different gas is introduced through shield 14, allowing improved gas isolation and quicker cycling of the gases.

Movement of shield 14, either before or during the gas flow, allows gas to be introduced at different planes within process chamber 12, parallel to the plane of substrate 8. The shield motion can be used to optimize the gas flow distribution of a particular ALD process.

As discussed previously, another role of shield 14 is to confine plasma 194 during processing (Fig. 13), which can result in heating of shield 14. To maintain the shield at an acceptable process temperature, a cooling/heating channel can be incorporated in the shield design. This also helps prevent deposition on shield 14.

Fig. 25 is a perspective cross-section of an embodiment of a shield assembly 302, including a shield cooling/heating channel 304, for ALD reactor 100 of Fig. 8. Shield assembly 302 includes some shield support legs 16, which are solid, attached to shield cap 196 at the base of shield 14. Similar to shield assembly 296 of Fig. 24, which includes gas channel 40, a cooling or heating fluid flows up into shield 14 through at least one hollow shield support leg 306, which extends through shield cap 196 into cooling/heating channel 304 in shield 14. Shield cooling/heating channel 304 is annular and runs about two-thirds of the way around the base of shield 14. The cooling or heating fluid flows down, out of shield 14, through at least one other hollow shield support leg (not shown), which is similar to hollow shield support leg 306.

Cooling or heating of shield 14 using a fluid flowing in cooling/heating channel 304 also allows improved control of the temperature of gases introduced into process chamber 12 through shield 14. Fig. 26 is a perspective cross-section of an embodiment of a shield assembly 308, including both shield gas channel 40 and shield cooling/heating channel 304, for ALD reactor 100 of Fig. 8. In the embodiment shown in Fig. 26, gas channel 40 is located above cooling/heating channel 304. Hollow shield support leg

306 extends through shield cap 196 into cooling/heating channel 304 to allow fluid flow. Hollow shield support leg 298 extends through shield cap 196 and cooling/heating channel 304 into gas channel 40 to allow gas introduction from shield 14 into process chamber 12 via gas flow orifices 300.

Practitioners will appreciate that shield assembly 308 could include alternative arrangements of gas channel 40 and cooling/heating channel 304, including multiple gas channels 40 and/or multiple cooling/heating channels 304.

Design of particular shield assembly embodiments is extremely flexible, and reactor 100 is designed to facilitate removal, replacement, and use of various shield assemblies. This allows the easy introduction of a shield assembly that might include gas delivery and cooling/heating (i.e., shield assembly 308), or only one of these (i.e., shield assemblies 296 or 302), or neither gas delivery nor cooling/heating, depending on the requirements of the customer and the process.

Electrostatic Chuck Assembly Design

ALD processes in the disclosed embodiments are ion-induced (see, for example, Application Serial No. 09/812,352, Application Serial No. 09/812,486, and Application Serial No. 09/812,285, referenced above), rather than thermally induced, through use of plasma 194 generated in process chamber 12 (Fig. 11 and Fig. 13). This allows deposition at lower temperatures than in conventional ALD systems, allowing replacement of conventional heated susceptors with an electrostatic chuck (ESC) assembly 106 to retain substrate 8. ESC assembly 106 may be further designed for improved temperature control and improved radio frequency (RF) power coupling.

Fig. 27A is a cutaway perspective view of an embodiment of an electrostatic chuck assembly 106 for ALD reactor 100 of Fig. 8. ESC assembly 106 includes in part, an electrostatic chuck (ESC) 6, a cooling plate 110, and a baseplate 112. Cooling plate 110 and baseplate 112 can be shaped as annuli with overlapping central orifices that together define an access port 310, which provides access to a central region of the underside of ESC 6.

Substrate 8 rests on an annular sealing lip 46, peripherally surrounding a top surface 50 of ESC 6. Annular sealing lip 46 holds substrate 8 above surface 50 defining a backside gas volume 48 bounded by surface 50, sealing lip 46, and the backside of substrate 8.

A backside gas is provided to gas volume 48 through a backside gas entry 312 to a backside gas valve 154. Gas valve 154 is located on the exterior underside of reactor 100 at the outer edge of baseplate 112 to provide easy access (Fig. 8 and Fig. 11). The backside gas flows along a backside gas line 54, which runs radially inward along a lower surface of baseplate 112. Gas line 54 curves upward through access port 310 and is attached to the center of the bottom surface of ESC 6 using a backside gas line flange 314. The backside gas flows through a backside gas passageway 56 centrally located in and extending through ESC 6 to gas volume 48. A backside gas line seal 316 inside flange 314 maintains the pressure of gas volume 48. The backside gas plays an important role in the temperature control of substrate 8.

Electrostatic chucks are usually made of a dielectric material (e.g., aluminum nitride AlN, or polyimide). ESC 6 may be designed to have its bulk material effects dominated by the Johnson-Rahbek (JR) effect rather than a coulombic effect, since the JR effect provides a stronger, more efficient electrostatic attraction. A JR ESC typically has a bulk resistivity between 10^8 and 10^{12} Ω -cm, while a coulombic ESC generally has a bulk resistivity greater than 10^{13} Ω -cm.

Embedded in the dielectric material of ESC 6, close to top surface 50, are at least two electrodes.

A first electrode 80 and a second electrode 82 are shaped as concentric annular plates made of a conductive material, for example, tungsten or molybdenum. First electrode 80 is biased using a first electrode terminal 318, which is coupled to first electrode 80 and extends down through ESC 6 into access port 310. Second electrode 82 is biased using a separate second electrode terminal (not shown). A DC "chucking" voltage is applied to both first electrode 80 and second electrode 82 to create an electrostatic attraction between substrate 8 and top surface 50 of ESC 6 to retain substrate 8 during processing. Simultaneously, RF bias power is coupled to each electrode 80 and 82 as well. The RF bias power provides the power for plasma and hence ion generation during modulated ion induced atomic layer deposition.

In addition to generating a plasma, the RF bias power also induces a slight negative potential (e.g., a DC offset voltage typically -10 V to -80 V at ≤ 150 W RF power and $0.1 - 1$ Torr pressure) on substrate 8. The magnitude of the potential should be ≤ 150 V. The induced voltage defines the ion energy of the positively charged ions in the plasma and attracts the positively charged ions toward the surface of substrate 8. The positively charged ions impinge on the wafer, driving the deposition reaction and improving the density of the deposited film.

A resistive heater 72 is also embedded in ESC 6. Resistive heater 72 is shaped as at least one coil or ribbon that winds throughout ESC 6 in a plane located about midway between electrodes 80 and 82 and the bottom of ESC 6. Heater 72 is controlled via at least one resistive heater terminal 320 coupled to heater 72. Terminal 320 extends down through ESC 6 into access port 310. Thus, ESC 6 is basically a dielectric substrate support with an embedded heater 72 and embedded electrodes 80 and 82 for DC biasing and RF power coupling.

ESC 6 is held in contact with cooling plate 110 using an annular clamp ring 178, which overlaps a clamp land 322 of a surrounding flange at the base of ESC 6. An ESC O-ring 324 creates a vacuum seal between ESC 6 and cooling plate 110. A plurality of clamp ring fasteners 180, each extending through clamp ring 178 into cooling plate 110, secure the connection between ESC 6 and cooling plate 110. A process kit 182, having an annular elbow shape, fully surrounds clamp ring 178 covering a top surface and a side surface of clamp ring 178. Process kit 182 includes a process kit bevel 202 used for centering a shadow ring 28 (Fig. 15) on process kit 182. Process kit 182 may be made of a dielectric material (e.g., aluminum oxide, aluminum nitride, or hard-anodized aluminum) to electrically isolate clamp ring fasteners 180 from ESC 6 and substrate 8. Process kit 182 also protects clamp ring 178 and fasteners 180 from process gases, facilitating cleaning of reactor 100 (Fig. 12).

Cooling plate 110 can be made (e.g., machined) from a variety of thermally conductive materials, for example, aluminum or stainless steel. An upper surface of cooling plate 110 is patterned to create a plurality of small area contacts 326 and a plurality of thermal breaks 184. Contacts 326, which have the form of ridges, contact the bottom surface of ESC 6. Thermal breaks 184 are gaps between ESC 6 and cooling plate 110, which increase the temperature difference between ESC 6 and cooling plate 110. The temperature of cooling plate 110 can be controlled using a fluid (e.g., water) flowing in a plurality of coolant channels 78. Coolant channels 78 are designed to allow the fluid to flow in a largely circular manner at various diameters of cooling plate 110.

A lower surface of cooling plate 110 is attached to an upper surface of baseplate 112. The upper surface of baseplate 112 forms the lower walls of coolant channels 78 in cooling plate 110. Baseplate 112, which may be made of aluminum, provides structural support for ESC assembly 106. Thermal breaks 184

of cooling plate 110 allow maintenance of a significant temperature difference between top surface 50 (which may be near 300 °C) of ESC 6 and a bottom surface of baseplate 112 (which is exposed to air and may be less than 50 °C).

One of a plurality of lift pins 108, which facilitate loading and unloading of substrate 8, is shown in retracted process position, with the tip of lift pin 108 below top surface 50 of ESC 6. Each lift pin 108 extends through a lift pin orifice 328, which includes a plurality of aligned orifices in baseplate 112, cooling plate 110, and ESC 6.

Alternative embodiments of ESC assembly 106 are possible. For example, in some embodiments, at least one peripheral ring of holes can be used to introduce the backside gas, rather than just a centrally located hole, as discussed in more detail below. In addition, in some embodiments, ESC 6 can be replaced with a conventional susceptor to facilitate ALD processes at higher temperatures.

Fig. 27B illustrates interdigitated electrodes 79 and 83, and Fig. 27C illustrates D-shaped electrodes 85 and 87, that may be used instead of the concentric annular plate electrodes 80 and 82 in Fig. 27A. Electrodes 85 and 87 may be solid or have an opening, such as shown by dashed lines. Practitioners will appreciate that various other embodiments of the electrodes are possible.

In one embodiment, the showerhead 172 (Fig. 23) is not grounded but is coupled to another RF source in a manner similar to the RF source coupling to the ESC electrodes in Fig. 7. The phase difference between the RF power applied to showerhead 172 and the RF power coupled to electrodes 80 and 82 in the ESC controls ion density and energy, with a difference of 180° creating the maximum ion density and energy. In another embodiment, the two RF sources have different frequencies.

Temperature Control of Electrostatic Chuck Assembly

Temperature control of ESC assembly 106 (Fig. 27A) is important for high quality atomic layer deposition. A uniform temperature across a substrate 8 resting on annular sealing lip 46 of ESC 6 promotes uniform chemisorption of precursors. If the temperature of substrate 8 is too high, decomposition or desorption of precursors may occur. If the temperature of substrate 8 is too low, either or both of the chemisorption and the deposition reactions will be impeded.

Fig. 28 is a schematic diagram of a control system 330 for electrostatic chuck (ESC) assembly 106 (Fig. 27A) of ALD reactor 100 of Fig. 8. Control system 330 may also be applied to various embodiments of pedestal 4 of ALD reactor 2 of Fig. 1. Control system 330 is an embodiment of control system 44 of Fig. 6, as discussed previously.

Control system 330 is used to establish and maintain a uniform temperature across substrate 8. As shown in Fig. 28, substrate 8 rests on an annular sealing lip 46 defining a backside gas volume 48 between substrate 8 and top surface 50 of ESC 6. A backside gas (e.g., Ar, He, etc.) is usually chosen from among the species in chamber 12 to prevent contamination in the deposited film. The backside gas flows from a backside gas source 52 along a backside gas line 54, through a backside gas passageway 56 in ESC 6, and into gas volume 48.

The backside gas improves the thermal contact between substrate 8 and ESC 6, by providing a medium for thermal energy transfer between substrate 8 and ESC 6. Heat transfer improves with increasing backside gas pressure, up to a saturation limit. Ranges for backside gas pressures are 3–20 torr, and typical ranges are 6–10 torr for good thermal conductivity and temperature uniformity across the substrate. Using the disclosed embodiments, a temperature uniformity across the substrate may be ≤ 5 °C. Above a backside

gas pressure of 5 torr, a uniformity of $\leq 15^\circ\text{C}$ is typically achieved. A pressure controller 58 maintains the backside gas at a constant pressure, thus ensuring constant heat transfer and uniform substrate temperature. In practice, annular sealing lip 46 may take the form of several islands scattered across top surface 50 of ESC 6. This introduces a leak rate of the backside gas that must be taken into account. The amount of direct contact between the chuck and the substrate can be virtually any amount, such as between 15-50%.

The temperature of substrate 8 is modulated by heating or cooling ESC 6. A temperature sensor 60 (e.g., a thermocouple or optical infrared sensor) is coupled via a sensor connection 62 to a temperature monitor 64 in a closed loop feedback control circuit 332. A temperature setpoint signal is also provided to monitor 64 via a setpoint electrical connection 334. A temperature controller 66 creates a signal that is amplified through a power amplifier or modulator 336 and applied via an electrical connection 70 to a resistive heater terminal 320 (Fig. 27A), which is coupled to a resistive heater 72 embedded in ESC 6. A coolant temperature and flow controller 74, as is widely known, controls the fluid from a coolant supply 76 as it flows in a plurality of coolant channels 78 in pedestal 4 (or in ESC assembly 106 in Fig. 12 and Fig. 13).

Control system 330 is designed to control the temperature of substrate 8, by heating and/or cooling, for a wide range of power and temperature. Temperature control can be accomplished by various techniques, including regulating the backside gas pressure, heating ESC 6 directly with resistive heater 72, or regulating the temperature and/or flow of fluid in coolant channels 78. The temperature of substrate 8 can thus be periodically or continuously varied during the deposition process to meet different process demands. Additional information regarding temperature control in atomic layer deposition may be found in related U.S. Application Serial No. 09/854,092, entitled "Method And Apparatus For Improved Temperature Control In Atomic Layer Deposition," filed May 10, 2001.

Alternative embodiments of control system 330 of Fig. 28 are possible. For example, the temperature control system of circuit 332 may have various embodiments. In addition, temperature sensor 60 may have various embodiments. Temperature sensor 60 may be a thermocouple that measures the temperature of ESC 6. Temperature sensor 60 may be a pyrometer device that optically measures the temperature of the backside of substrate 8. Or, temperature sensor 60 could take other equivalent forms.

In some embodiments of control system 330 of Fig. 28, an alternative energy source may be included as another option to control the temperature of substrate 8. Fig. 29 is a schematic diagram of a control system 338, including an alternative energy source 340, for pedestal 4 of reactor 2 (Fig. 1) or for ESC assembly 106 (Fig. 27A) of ALD reactor 100 (Fig. 8). Control system 338 is similar to control system 44 (Fig. 6) and control system 330 (Fig. 28), as discussed previously. Alternative energy source 340 is located outside of pedestal 4 (or ESC assembly 106) near the top of chamber 12 and may include radiation from lamps, a plasma, or another source. Alternative energy source 340 could be controlled, for example, by regulating the power to the lamps or plasma. Alternative energy source 340 could be used alone, or in conjunction with one or more of resistive heater 72, the fluid in coolant channels 78, or the pressure of the backside gas in gas volume 48.

In some embodiments, an additional cooling source may be added to control system 330 of Fig. 28 to improve the cooling capacity and/or performance. The additional cooling source could be a refrigeration system, a heat pipe, a refrigerated liquid or gas coolant system, or other equivalent system.

In some embodiments of control system 330 of Fig. 28, the backside gas may be introduced to gas volume 48 through multiple orifices rather than just a centrally located orifice. Fig. 30 is a perspective

view of an embodiment of a portion 342 of an ESC assembly 106 (Fig. 27A) for ALD reactor 100 of Fig. 8. ESC 6 includes a central orifice 344 as well as a peripheral ring of orifices 346 located near the periphery of substrate 8. Various embodiments of ESC 6 may include either or both of orifice 344 and orifices 346. Orifices 346 result in improved pressure uniformity between substrate 8 and ESC 6, which results in improved temperature uniformity across substrate 8. An additional peripheral ring of orifices 347 can be added outside of orifices 346 to ensure a constant pressure gradient at the edge of substrate 8. The additional ring of orifices would also serve as an edge purge to prevent reactive gases from entering gas volume 48 (Fig. 28) and causing deposition on the backside of substrate 8.

In some embodiments of control system 330 of Fig. 28, pressure controller 58 may be replaced by, for example, a flow regulator such as a metering valve or mass flow controller. In still other embodiments, an actuation valve can be added between pressure controller 58 and backside gas volume 48 to isolate pressure controller 58 and gas source 52 from process chamber 12 during a substrate transfer. This valve may additionally be used to stop the flow of backside gas to reduce its pressure, allowing the substrate to “de-chuck” without “popping” (shifting) when electrodes 80 and 82 in ESC 6 are de-powered. This valve may additionally be used in conjunction with a pump to more quickly reduce the backside gas pressure before “de-chucking” substrate 8.

Practitioners will appreciate that various other embodiments of control system 330 and its various constituents are possible.

Electrical Biasing and Plasma Generation Using Electrostatic Chuck Assembly

Fig. 31 is a schematic diagram of a circuit 348 for electrical biasing of electrostatic chuck (ESC) 6 of ESC assembly 106 (Fig. 27A) of ALD reactor 100 of Fig. 8. Circuit 348 may also be applied to various embodiments of ESC 6 of pedestal 4 of ALD reactor 2 of Fig. 1. Circuit 348 is an alternative embodiment to circuit 84 of Fig. 7, as discussed previously.

As shown in Fig. 31, ESC 6 includes at least a first electrode 80 and a second electrode 82. One possible embodiment of the electrode geometry of first and second electrodes 80 and 82 (shown schematically in Fig. 31) is shown in Fig. 27A, where first and second electrodes 80 and 82 are shown as concentric annular plates. A double D (i.e., mirror imaged) configuration or interdigitated configuration for electrodes 80 and 82 can also be used, as previously mentioned. In Fig. 31, first and second electrodes 80 and 82 are each biased with a DC voltage. RF bias power is also coupled to both electrodes 80 and 82. Embedding electrodes 80 and 82 in ESC 6 allows improved RF power coupling to substrate 8 with maximum uniformity and minimal power loss, compared to applying RF power to cooling plate 110 (or baseplate 112) upon which ESC 6 sits (Fig. 27A). This is because electrodes 80 and 82 in ESC 6 are close to substrate 8, while cooling plate 110 (and baseplate 112) are comparatively far from substrate 8.

First electrode 80 and second electrode 82 are biased with different DC potentials to provide the “chucking” action that holds substrate 8 to ESC 6 prior to plasma ignition and during deposition. As shown in Fig. 31, first electrode 80 is coupled via a serial coupling of a first inductor 88 and a first load resistor 350 to one terminal of a DC power supply 86. Second electrode 82 is coupled via a serial coupling of a second inductor 90 and a second load resistor 352 to the other terminal of DC power supply 86.

A third capacitor 354 is coupled between one terminal of inductor 88 and a ground terminal 94. A fourth capacitor 356 is coupled between the other terminal of inductor 88 and ground terminal 94. A fifth capacitor 358 is coupled between one terminal of inductor 90 and ground terminal 94. A sixth capacitor

360 is coupled between the other terminal of inductor 90 and ground terminal 94. Inductor 88 and capacitors 354 and 356 together form an RF trap circuit 362, which filters RF from the DC bias. Similarly, inductor 90 and capacitors 358 and 360 together form another RF trap circuit 362.

RF power is also supplied to both first electrode 80 and second electrode 82 using an RF generator 92 with one terminal coupled to ground terminal 94. A third inductor 364 is coupled between the other terminal of RF generator 92 and one terminal of a first variable capacitor 366. The other terminal of variable capacitor 366 is coupled to one terminal of a first capacitor 96 and to one terminal of a second capacitor 98. The other terminal of capacitor 96 is coupled to first electrode 80. The other terminal of capacitor 98 is coupled to second electrode 82. A second variable capacitor 368 is coupled across the terminals of RF generator 92, between one terminal of inductor 364 and ground terminal 94. Inductor 364 and capacitors 366 and 368 together form an RF impedance matching circuit 370, which minimizes the reflected power to RF generator 92.

Circuit 348 of Fig. 31 allows simultaneous application of a DC "chucking" voltage and of an RF power for plasma generation during processing. The same RF power is used to create plasma 194 above substrate 8 (Fig. 13) and to generate a negative, induced DC bias on substrate 8. RF power can be used since the breakdown voltage required to generate plasma 194 using RF power is far lower than in the DC case (e.g., 100 V vs. 300–400 V) for a given Paschen curve of pressure-distance product ($P \times d$). In addition, a stable DC bias can be induced using RF power. Of course, it is possible to generate plasma 194 using a high DC voltage instead of RF power, with appropriate modifications to the biasing hardware (see, for example, the discussion of Fig. 40 below).

In Fig. 31, coupling RF power to electrodes 80 and 82 allows a uniform potential to build across substrate 8 while employing low RF powers, for example, 50 W to 150 W, which is less than the 350 W to 600 W required in conventional plasma reactors. The frequency of the RF bias power can be 400 kHz, 13.56 MHz, or higher (e.g., 60 MHz, 200 MHz). The low frequency, however, can lead to a broad ion energy distribution with high energy tails which may cause excessive sputtering. The higher frequencies (e.g., 13.56 MHz or greater) lead to tighter ion energy distributions with lower mean ion energies, which is favorable for modulated ion-induced ALD deposition processes. The more uniform ion energy distribution occurs because the bias polarity switches before ions can impinge on substrate 8, such that the ions see a time-averaged potential.

In conventional plasma reactors, RF power is applied to the top boundary of the process chamber, usually a showerhead. This causes sputtering of the top boundary, which is a major source of impurity incorporation (typically aluminum or nickel) and/or particulate incorporation in conventionally deposited films. The sputtering also transfers kinetic energy to the reactor structure, heating it considerably and requiring active cooling of the reactor structure.

In the present embodiments, RF power is applied to electrodes 80 and 82 (Fig. 31) embedded in ESC 6 of ESC assembly 106 of ALD reactor 100 (Fig. 12), rather than to showerhead 172 (Fig. 13). This minimizes sputtering of showerhead 172 and allows better control of the bias induced on substrate 8. It also avoids excessive heating of chamber lid 10, minimizing any cooling requirements.

Referring to Fig. 13, showerhead 172 and shield 14 are grounded so that the higher plasma sheath voltage drop is localized mostly on substrate 8 where deposition takes place. This is because the voltage ratio $V_{\text{hot}}/V_{\text{cold}}$ is proportional to the respective electrode areas according to $(A_{\text{cold}}/A_{\text{hot}})^n$, where n is greater than one. V_{hot} is the plasma sheath voltage drop at the powered, or "hot," electrode, that is, ESC 6 of ESC

assembly 106. V_{cold} is the voltage drop at the non-powered, or "cold," electrode, that is, showerhead 172 and shield 14. The combined areas of showerhead 172 and shield 14 can be jointly considered as the area of the cold electrode. This is because the small volume of process chamber 12 results in a showerhead 172 to ESC 6 spacing that is small (nominally 0.3 to 0.6 inches) so that the powered electrode can "see" showerhead 172 and shield 14 as a single ground reference. Taken together, these combined areas are larger than the area of substrate 8, or the area of the hot electrode. Thus, for this reactor, $A_{\text{cold}}/A_{\text{hot}} > 1$.

In addition, by applying RF power to ESC 6 via electrodes 80 and 82 (Fig. 31), a low RF power can be used to simultaneously generate plasma 194 (Fig. 13) and to keep the energy of the impinging ions from plasma 194 low and controlled. The ion energy is given by $E = e|V_p| + e|V_{\text{bias}}|$, where V_p is the plasma potential and V_{bias} is the bias voltage induced on substrate 8. The ion energy should be ≤ 150 eV, and preferably between 10–80 eV, to drive the deposition reaction. The magnitude of V_{bias} should be ≤ 150 V, and preferably V_{bias} should be between –10 and –80 V, to prevent sputtering of the deposited layer. The magnitude of V_p is typically 10–30 V.

The induced bias voltage is controlled by the applied RF power. The induced bias voltage increases with increasing RF power and decreases with decreasing RF power. Increasing the RF power also generally increases the number of ions generated.

Controlling the RF power also controls the density of ions in the plasma. Higher RF powers are required for larger substrate diameters. The preferred power density is ≤ 0.5 W/cm², which equates to approximately ≤ 150 W for a 200 mm substrate. Power densities ≥ 3 W/cm² (greater than about 1000 W for a 200 mm diameter substrate) may lead to undesired sputtering of the deposited film.

Referring to Fig. 13, cooling plate 110 and baseplate 112 are grounded. Therefore, each clamp ring fastener 180 is also grounded. Process kit 182, which is made of an insulating material, electrically shields fasteners 180 so that plasma 194 is not affected by the ground voltage of fasteners 180.

Plasma 194 can be controlled in a variety of ways. For example, plasma 194 can be controlled by varying the applied RF power. In some alternative embodiments of circuits for electrical biasing of ESC 6 of ALD reactor 100 (Fig. 12 and Fig. 13), a switch may be included, for example, in RF impedance matching circuit 370 or with RF generator 92 (Fig. 31). Fig. 32 is a schematic diagram of a circuit 372, including an RF match switch 374 in RF impedance matching circuit 370, for electrical biasing of ESC 6. Fig. 33 is a schematic diagram of a circuit 376, including an RF supply switch 378 in an RF power supply 380 (which also includes RF generator 92), for electrical biasing of ESC 6. Circuit 372 (Fig. 32) and circuit 376 (Fig. 33) are similar to circuit 348 (Fig. 31), except for switches 374 and 378. Switches 374 and 378 can be opened to isolate RF generator 92, or switches 374 and 378 can be closed to apply RF power to electrodes 80 and 82. Switches 374 and 378 enable a plasma response time in the 100 ms time range.

Plasma 194 (Fig. 13) can also be controlled by varying gas pressure while using, for example, circuit 348 of Fig. 31 with an RF power constantly applied to electrodes 80 and 82. Referring to Fig. 15, Fig. 16, and Fig. 17, as discussed previously, shield 14 forms a shield conductance upper path 22 with showerhead 172 and chamber lid 10. Shield 14 also forms a shield conductance lower path 24 with shadow ring 28. The conductances of upper and lower paths 22 and 24 are varied by precision movement of shield 14 by linear motor 122 (Fig. 8).

The conductances of upper and lower paths 22 and 24 directly affect the pressure in process chamber 12 and can be used to vary that pressure. For example, a high pressure (i.e., relative to the pressure of annular pumping channel 20) can be established in chamber 12 using a low conductance process

shield position 210 as shown in Fig. 15. High pressure will strike plasma 194 (Fig. 13) given a favorable ambient in chamber 12. A low pressure can be established in chamber 12 using a purge shield position 214, as shown in Fig. 17, to expose chamber 12 to annular pumping channel 20. Low pressure will effectively terminate plasma 194 since not enough gas phase collisions will occur to sustain plasma 194. Applying RF power to electrodes 80 and 82 at pressures that will not strike or sustain plasma 194 will cause 100% reflection of the output power from RF generator 92 (Fig. 31). Thus, RF generator 92 should be capable of absorbing this power without detrimental effects.

Plasma 194 (Fig. 13) can also be controlled by a combination of varying gas pressure and applied RF power. For example, plasma 194 may be ignited by a high pressure and favorable ambient in chamber 12. Plasma 194 may be terminated by a switch, such as switch 374 in circuit 372 of Fig. 32 or switch 378 in circuit 376 of Fig. 33.

Practitioners will appreciate that various other embodiments of circuit 348 of Fig. 31 and its various constituents, for electrical biasing of ESC 6, are possible. For example, multiple RF sources may be utilized.

ALD Processes: Background and Novel Processes

Fig. 34 is a schematic illustration of a conventional ALD process. In a typical ALD cycle, which usually includes four steps, each precursor (or reactant) is introduced sequentially into the chamber, so that no gas phase intermixing occurs. First, a first gaseous precursor 382 (labeled Ax) is introduced into the deposition chamber, and a monolayer of the reactant is chemisorbed (or physisorbed) onto the surface of a substrate 8 forming a chemisorbed precursor A 384 as shown in Fig. 34(a). A free ligand x 386 is created by the chemisorption of precursor Ax 382. Second, excess gaseous precursor Ax 382 and ligands x 386 are pumped out, possibly with the aid of an inert purge gas, leaving the monolayer of chemisorbed precursor A 384 on substrate 8 as shown in Fig. 34(b).

Third, a second gaseous precursor 388 (labeled By) is introduced into the deposition chamber. Precursor By 388 reacts with chemisorbed precursor A 384 on substrate 8 as shown in Fig. 34(c) in a self-limiting surface reaction. The self-limiting reaction halts once initially adsorbed precursor A 384 fully reacts with precursor By 388. Fourth, excess gaseous precursor By 388 and any reaction by-products are pumped out, again possibly with the aid of an inert purge gas, leaving behind an AB monolayer 390 of the desired thin film as shown in Fig. 34(d). A desired film thickness is obtained by repeating the deposition cycle as necessary. The film thickness can be controlled to atomic layer (i.e., angstrom scale) accuracy by simply counting the number of deposition cycles.

ALD processes, however, are slower than traditional deposition techniques such as CVD and PVD. In order to improve throughput, shorter deposition cycles are desirable. One way to shorten the deposition cycle is to shorten the durations of the individual precursor and pump/purge steps. The individual pulse lengths, however, cannot be arbitrarily decreased. The first precursor pulse must be long enough to form an adsorbed layer of the first precursor on the substrate. The second precursor pulse must be long enough to allow complete reaction between the first and second precursors. The pump/purge pulses in between the precursor pulses must be long enough so that gas phase intermixing of the precursors does not occur. Gas phase intermixing can lead to gas phase reactions and/or particle formation, each of which can cause quality and reliability problems in the deposited film.

Fig. 35 is a schematic illustration of a novel ALD process. One deposition cycle includes two steps, rather than four, which improves process throughput and repeatability. In the base process, a substrate 8 is maintained at a precise temperature that promotes chemisorption rather than decomposition.

In the first step, a gaseous precursor 392 is introduced into the process chamber. Gaseous precursor 392 includes the desired thin film species (P) bonded with a plurality of ligands (L). Species P may be a single element (e.g., Ti, W, Ta, Cu) or a compound (e.g., TiN_x , TaN_x , or WN_x). In the novel ALD process, a molecule of gaseous precursor 392 interacts with a surface bond 394 to form a chemisorbed precursor 396 via a chemical bonding process that may create a plurality of free ligands 398 as shown in Fig. 35(a). As a result of the first step, a monolayer of chemisorbed precursor 396 is formed on substrate 8 as shown in Fig. 35(b).

In the second step, an inert purge gas is introduced into the process chamber to purge excess gaseous precursor 392. The purge gas may include, for example, argon (Ar), diatomic hydrogen (H_2), and other optional species such as helium (He). RF power is applied (e.g., using a computer synchronized switch) during this second step to generate a plasma 194 in the process chamber, or the plasma is struck by an increased gas pressure under constant RF power. As shown in Fig. 35(c), plasma 194 includes a plurality of energetic ions 400 (e.g., Ar^+ ions) and a plurality of reactive atoms 402 (e.g., H atoms). Some of reactive atoms 402 may actually be ions.

Ions 400 and atoms 402 impinge on the surface of substrate 8. Energetic ions 400 transfer energy to substrate 8, allowing reactive atoms 402 to react with chemisorbed precursor 396 and to strip away unwanted ligands (which form a plurality of volatile ligands 404) in a self-cleaning process. Reactive atoms 402, in conjunction with energetic ions 400, may thus be considered to act as a "second" precursor. When the plasma power is terminated, a monolayer 406, usually about one atomic layer of the desired species P, is left on substrate 8 as shown in Fig. 35(d). This two-step deposition cycle can be repeated as needed until the desired film thickness is achieved. The film thickness deposited per cycle depends on the deposited material. Typical film thicknesses range from 10–150 Å.

Typical precursors for tantalum (Ta) compounds include PDEAT [pentakis(diethylamido)tantalum], PEMAT [pentakis(ethylmethylamido)tantalum], $TaBr_5$, $TaCl_5$, and TBTDDET [t-butylimino tris(diethylamino)tantalum]. Typical precursors for titanium (Ti) compounds include $TiCl_4$, TDMAT [tetrakis(dimethylamido)titanium], and TDEAT [tetrakis(diethylamino)titanium]. Typical precursors for copper (Cu) compounds include CuCl and Cupraselect® [(trimethylvinylsilyl)hexafluoroacetylacetonato copper I]. Typical precursors for tungsten (W) compounds include $W(CO)_6$ and WF_6 . In contrast to conventional ALD processes, organometallic precursors can be used in novel ALD processes.

The purge pulse includes gas, or gases, that are inert (e.g., argon, hydrogen, and/or helium) to prevent gas phase reactions with gaseous precursor 392. Additionally, the purge pulse can include the same gas, or gases, needed to form energetic ions 400 (e.g., Ar^+ ions) and reactive atoms 402 (e.g., H atoms). This minimizes the gas switching necessary for novel ALD processes. Acting together, reactive atoms 402 react with chemisorbed precursor 396, while energetic ions 400 provide the energy needed to drive the surface reaction. Thus, novel ALD processes can occur at lower temperatures (e.g., $T < 300^\circ C$) than conventional ALD processes (e.g., $T \approx 400\text{--}500^\circ C$). This is especially important for substrates that already include low thermal stability materials, such as low-k dielectrics.

Since the activation energy for the surface reaction is provided by energetic ions 400 created in plasma 194 above substrate 8, the reaction will not generally occur without the energy provided by ion bombardment because the process temperature is kept below the temperature required for thermal activation. Thus, novel atomic layer deposition processes are ion-induced, rather than thermally induced.

- 5 The deposition reaction is controlled by modulation of the energy of energetic ions 400, by modulation of the fluxes of energetic ions 400 and reactive atoms 402 impinging on substrate 8, or by modulation of both energy and fluxes. The energy (e.g., 10 eV to 100 eV) of energetic ions 400 should be high enough to drive the surface reaction, but low enough to prevent significant sputtering of substrate 8.

- Timing diagrams for (a) a typical prior art ALD process and (b) a novel ALD process are compared in Fig. 36. Fig. 36(a) shows that one deposition cycle in a conventional ALD process includes a first precursor pulse 408, a purge/pump pulse 410, a second precursor pulse 412, and another purge/pump pulse 410. Each pulse is followed by a delay 414, which has a duration that is usually non-zero. Delays 414, during which only pumping occurs and no gases flow, are additional insurance against gas phase intermixing of first precursor pulse 408 and second precursor pulse 412. Delays 414 also provide time to switch gases with conventional valve systems.

The durations of first and second precursor pulses 408 and 412 may be between 200 ms and 15 sec. The duration of purge/pump pulses 410 may be 5–15 sec. The durations of delays 414 may be 200 ms to 5 sec. This results in deposition cycles from 11 sec to 75 sec. Thus, a 50 cycle deposition process could take over one hour.

- 20 Fig. 36(b) shows two deposition cycles in the novel ALD process. One deposition cycle includes a first precursor pulse 416 and a purge gas pulse 418. Each pulse is followed by a delay 420. The elapsed time of one deposition cycle is significantly shorter in accordance with the novel process when compared to conventional ALD processes, thereby increasing process throughput.

- Process throughput can be further increased if delays 420 have zero length. Zero-length delays can be accomplished using three-way valves (in particular showerhead three-way valve 148 of Fig. 8) or a similar configuration of on/off valves and fittings, which allow fast gas switching. Delays 420 of zero length are further facilitated in novel ALD processes by effective use of purge gas pulse 418, which may include a mixture of more than one gas. For example, the purge gas may include the “second” precursor source gas(es) (i.e., as shown in Fig. 35(c), reactive atoms 402, acting in conjunction with energetic ions 400, created during purge gas pulse 418). Additionally, the carrier gas for the first precursor (i.e., flowing during first precursor pulse 416) may be one of the source gases of the “second” precursor.

- Practitioners will appreciate that alternative embodiments of novel ALD processes are possible. For example, in some embodiments, multiple precursors for compound thin films might be employed. In other embodiments, the deposition cycle of Fig. 36(b) might begin with a purge gas pulse 418, including a plasma, used as an in-situ clean to remove carbon-containing residues, native oxides, or other impurities. In these embodiments, reactive atoms 402 (e.g., H atoms in Fig. 35(c)) react with carbon and oxygen to form volatile species (e.g., CH_x and OH_x species). Energetic ions 400 (e.g., Ar^+ and/or He^+ ions in Fig. 35(c)) improve dissociation (e.g., of H_2) and add a physical clean (e.g., via sputtering by Ar^+ ions generated in the plasma). In still other embodiments, reactive atoms 402 may not be needed and plasma 194 may not include reactive atoms 402.

Additional information regarding in-situ cleaning in atomic layer deposition may be found in related U.S. Provisional Application Serial No. 60/255,812, entitled “Method For Integrated In-Situ

Cleaning And Subsequent Atomic Layer Deposition Within A Single Processing Chamber,” filed December 15, 2000.

Alternative Novel ALD Processes

The novel ALD process described previously may be modified to further increase performance.

5 Alternative novel ALD processes may address faster purging of precursors, rapid changes in the conductance of the process chamber, state-based changes from one step to the next, self-synchronization of the process steps, and/or various plasma generation and termination options. Such alternatives can be used to further decrease the length of a deposition cycle, thereby increasing throughput.

For example, in some novel ALD process embodiments, it is desirable to quickly purge a gaseous precursor 392 from the process chamber after formation of a monolayer of chemisorbed precursor 396 on substrate 8 (Fig. 35(b)). This can be accomplished using the in-process tunable conductance achieved by shield 14 (Fig. 13), which can be moved during the deposition cycle. Referring to Fig. 15, Fig. 16, and Fig. 17, as discussed previously, shield 14 forms shield conductance upper path 22 with showerhead 172 and chamber lid 10. Shield 14 also forms shield conductance lower path 24 with shadow ring 28. The conductances of upper and lower paths 22 and 24 are varied by precision movement of shield 14 by linear motor 122 (Fig. 8).

It is possible, therefore, to rapidly increase the chamber conductance by lowering shield 14 after exposing substrate 8 to gaseous precursor 392. For example, a purge shield position 214 may be used (Fig. 17). Lowering shield 14 opens up shield conductance upper and lower paths 22 and 24 to annular pumping channel 20. The low pressure of pumping channel 20 will hasten removal of excess gaseous precursor 392, and by-products such as free ligands 398 (Fig. 35(b)), from process chamber 12. Simultaneously, the purge gas (e.g., Ar, H₂, and/or He) is flowed to assist in purging excess gaseous precursor 392 and by-products from chamber 12. Lowering shield 14 also leads to a drop in the pressure in chamber 12 through exposure of chamber 12 to annular pumping channel 20. Shield 14 can then be moved back up, for example, to a position similar to shield position 212 of Fig. 16, to decrease the conductance and raise the pressure in chamber 12 (assuming constant gas flow) in order to strike plasma 194 (Fig. 35(c)).

In particular, plasma 194 can be generated while using, for example, circuit 348 of Fig. 31. Application of RF power may be synchronized (e.g., by computer control) with the position of shield 14 (Figs. 15-17) to generate plasma 194 in chamber 12 (Fig. 13). Alternatively, if RF bias power is constantly applied to electrodes 80 and 82 using circuit 348 (Fig. 31), high pressure (i.e., relative to the pressure of annular pumping channel 20) in process chamber 12 can be used to trigger plasma 194 (Fig. 13). Low pressure (i.e., near the pressure of annular pumping channel 20) will effectively terminate plasma 194 since not enough collisions will occur to sustain plasma 194.

Fig. 37 shows timing diagrams for an alternative ALD process embodiment, as discussed above. Fig. 37(a) shows two deposition cycles including a first precursor pulse 416 followed by a purge gas pulse 418 with zero length delays after each pulse. Fig. 37(b) shows the corresponding chamber conductance. Each one of a plurality of low conductance periods 422 (corresponding to raised shield positions) is separated from another by one of a plurality of high conductance periods 424 (corresponding to lowered shield positions). High conductance periods 424 occur at the beginning and end of each purge gas pulse 418 to assist in purging chamber 12 (Fig. 13) of resident gases.

Fig. 37(c) shows the corresponding pressure in chamber 12 (Fig. 13). A low conductance period 422 results in a high pressure period 426. A high conductance period 424 results in a low pressure period 428. Fig. 37(c) also shows a plurality of "plasma on" periods 430 and a plurality of "plasma off" periods 432. Plasma on periods 430 occur during each high pressure period 426 during purge gas pulses 418. As discussed, the RF power to generate plasma 194 (Fig. 13) may be synchronized with the shield position. Alternatively, the plasma can be ignited by high pressure (in the presence of the purge gas) and terminated by low pressure, while RF bias power is constantly supplied to electrodes 80 and 82 embedded in ESC 6 (Fig. 31).

Conventional ALD hardware and processes rely on the precise timing of the individual precursor pulses 408 and 412 and purge/pump pulses 410 (Fig. 36 (a)) to decrease the deposition cycle length and ensure proper process performance. These time-based processes rely on several assumptions including that steady state conditions exist, that all ALD reactors behave similarly, and that all gases and processes are "on time."

In contrast, some novel ALD process embodiments can use a state-based approach, rather than a time-based approach, to synchronize the individual pulses. This can provide self-synchronization of the individual pulses for improved process speed, control, and reliability. Instead of introducing a next gas pulse (with a fixed duration) a predetermined time after the introduction of the previous fixed duration gas pulse, subsequent gas pulses can be triggered based upon a change in the pressure state of process chamber 12 (Fig. 13). This can be accomplished using a pressure switch mounted in chamber body 18 capable of sensing changes in the pressure of process chamber 12. The pressure can be modulated via the in-process tunable conductance, achieved by a shield 14 that can be moved during the deposition cycle, as described previously.

Fig. 38 shows timing diagrams for another alternative embodiment of a novel ALD process. The ALD process of Fig. 38 is similar to the ALD process of Fig. 37, but it has an alternate plasma termination technique. Accordingly, to avoid redundancy, the discussion focuses on differences in the embodiments.

In the ALD process of Fig. 38, shield 14 is lowered only after each precursor pulse 416 to assist in purging excess gaseous precursor 392 and free ligands 398 from chamber 12 (see also Fig. 17 and Fig. 35 (b)). The number of high conductance periods 424 in Fig. 38(b), corresponding to low pressure periods 428 in Fig. 38 (c), is reduced. Thus, a low conductance period 434 in Fig. 38(b) (corresponding to a high pressure period 436 in Fig. 38(c)) extends from purge gas pulse 418 into the following precursor pulse 416 in Fig. 38(a). In this embodiment, the plasma is ignited by, or synchronized with, the high pressure in chamber 12 (Fig. 13). Plasma on periods 430 occur during each high pressure period 436 during purge gas pulses 418. Plasma 194 (Fig. 13) is terminated for subsequent plasma off periods 432 (during precursor pulses 416) by a means other than pressure change, which may include, for example, disconnecting the RF power using a switch or setting the RF output power to zero. A switch could be located, for example, in RF impedance matching circuit 370 or in RF power supply 380 (Fig. 32 and Fig. 33). Actuation of such a switch would be synchronized with the deposition steps by, for example, a computer.

Novel Chemisorption Technique for ALD Processes

The chemisorption of a gaseous precursor (e.g., precursor 392 in Fig. 35(a)) onto a substrate 8 may be improved by biasing substrate 8 during first precursor pulse 416 (Fig. 36(b)). As discussed previously with reference to Fig. 35(a), when a molecule of gaseous precursor 392 arrives at substrate 8, which is

heated, a weakly bonded ligand will cleave off of the molecule, forming free ligand 398. This actually leaves the precursor molecule with a net charge (either positive or negative). An opposite-polarity, low DC bias (e.g., $|50 \text{ V}| < |V_{\text{bias}}| < 0 \text{ V}$) applied to substrate 8 will attract the charged precursor molecule to substrate 8 and orient it so that the desired atom is bonded to substrate 8 to form chemisorbed precursor 396. The lowest possible bias (e.g., $|10 \text{ V}| < |V_{\text{bias}}| < 0 \text{ V}$) that generates a moment on the charged precursor molecule is desirable to correctly orient the charged precursor molecule with minimal charging of substrate 8.

This novel chemisorption technique for ALD processes promotes uniform and complete (i.e., saturated) chemisorption with a specified orientation on dielectric and metallic surfaces so that high quality, reproducible layer-by-layer growth can be achieved using ALD. The novel chemisorption technique is particularly effective for the first few precursor monolayers, where, in the absence of this technique, precursor molecules may chemisorb with a random orientation. This method is also particularly effective in the case of organometallic precursors such as those mentioned previously.

Fig. 39 is a schematic illustration of the novel chemisorption technique for ALD processes to deposit thin films, for example, for copper interconnect technology. Two thin films used in copper interconnect technology are a barrier/adhesion layer and a copper seed layer. Fig. 39(a) illustrates chemisorption of TaN, a typical barrier/adhesion layer material. In the case of a precursor TBTDET 438, the Bu^1 ligand may cleave. A now negatively charged precursor 440 then orients with a negatively charged nitrogen 442 (e.g., the N^{-1}) toward substrate 8, which is positively biased, for chemisorption. If an NEt_2 ligand is cleaved instead, then the Ta becomes positively charged and a negative bias applied to substrate 8 would orient the Ta toward substrate 8 for chemisorption.

Fig. 39(b) illustrates chemisorption of Cupraselect® (CuhfacTMVS), a typical copper seed layer material. In the case of a precursor CuhfacTMVS 444, the TMVS ligand is cleaved. A now positively charged precursor 446 then orients with a positively charged copper 448 (e.g., the Cu^{+1}) toward substrate 8, which is negatively biased, for chemisorption.

In some embodiments, the novel chemisorption technique may include an in-situ clean prior to introduction of the first precursor to promote high quality film deposition. As discussed above in reference to Fig. 36(b), a purge gas pulse 418 (e.g., including Ar, H_2 and/or He) can be used as an in-situ clean to remove carbon-containing residues, native oxides, or other impurities (see, for example, Application Serial No. 60/255,812, referenced above). Removing native oxides from metal layers is especially important for low resistance and good mechanical adhesion of the film to substrate 8 (Fig. 39). H atoms can react with carbon and oxygen to form volatile species (e.g., CH_x and OH_x species). Ar^+ or He^+ ions improve dissociation (e.g., of H_2) and add a physical clean (e.g., via sputtering by Ar^+ ions generated in the plasma). The gas ratios can be tailored to alter the physical versus chemical components of the in-situ clean.

Fig. 40 is a schematic diagram of a circuit 450 for electrical biasing of ESC 6 of ALD reactor 100 (Fig. 12) for the novel chemisorption technique described above. The use of ESC 6 helps provide a uniform bias to substrate 8 (Fig. 39). Circuit 450 of Fig. 40 is similar to circuit 372 of Fig. 32 and circuit 376 of Fig. 33. Accordingly, to avoid redundancy, the discussion will focus on differences between circuit 450 and circuits 372 and 376.

In Fig. 40, with the RF power from RF generator 92 decoupled by opening an RF power switch 452, a first DC power supply 454 and a second DC power supply 456, which are serially coupled matching supplies, perform the function of DC power supply 86 in Figs. 32 and 33 to maintain the potential

difference between electrodes 80 and 82. This potential difference provides the "chucking" action that holds substrate 8 (Fig. 39) to ESC 6. Serially coupled between the common node (labeled A) of DC power supplies 454 and 456 and a ground terminal 458 are a current suppression resistor 460, a DC power switch 462, and a DC reference voltage source 464. Ground terminal 458 may be the same ground reference as ground terminal 94.

With DC power switch 462 closed, the reference voltage of electrodes 80 and 82 (and therefore of substrate 8 during chemisorption as shown in Fig. 39) is established by DC reference voltage source 464. Current suppression resistor 460 limits the current from DC reference voltage source 464. DC reference voltage source 464 is capable of providing a positive or negative voltage, as needed for biasing substrate 8 (Fig. 39). The voltage level provided by DC reference voltage source 464 may additionally reduce the time required to chemisorb a complete monolayer. This may allow a reduction in the duration of first precursor pulse 416 (Fig. 36(b)) and/or a reduction in the precursor partial pressure during first precursor pulse 416.

Once chemisorption is complete, DC power switch 462 is opened to isolate voltage source 464 and to electrically float first and second DC power supplies 454 and 456. RF power switch 452 is closed to reconnect RF generator 92. The remainder of the ALD process continues as described previously.

In some embodiments of ALD processes, it is possible to use a circuit similar to circuit 450 of Fig. 40 to generate plasma 194 above substrate 8 (Fig. 13) by biasing ESC 6 using a high DC voltage (e.g., 500 V or higher). In this case, RF generator 92, RF impedance matching circuit 370, and capacitors 96 and 98 would not be used. DC reference voltage source 464 would supply at least two distinct voltages, or switch 462 would alternate between two distinct voltage sources. The first voltage would be a low DC voltage coupled to electrodes 80 and 82 during plasma off periods 432 (Fig. 37). The low DC voltage might be zero volts, or a non-zero low voltage used to orient precursor molecules for improved chemisorption as discussed above. The second voltage would be a high DC voltage coupled to electrodes 80 and 82 during plasma on periods 430 (Fig. 37) to generate plasma 194.

The novel ALD reactor is particularly suitable for thin film deposition, such as barrier layer and seed layer deposition, but the teachings herein can be applied to many other types of reactors and many other types of thin films (e.g., low-k dielectrics, gate dielectrics, optical films, etc.). The foregoing embodiments of the ALD reactor, and all its constituent parts, as well as the ALD processes disclosed herein are intended to be illustrative and not limiting of the broad principles of this invention. Many additional embodiments will be apparent to persons skilled in the art. The present invention includes all that fits within the literal and equitable scope of the appended claims.

CLAIMS

We claim:

1. A system comprising:

5 a deposition process chamber defined by at least in part by a pedestal, a chamber lid offset in a particular dimension from the pedestal, and a movable shield surrounding at least a portion of the pedestal and at least a portion of the lid;
wherein the shield moves back and forth in the particular dimension.

10 2. The system of claim 1, wherein the system is a deposition system.

3. The system of claim 1, wherein the process chamber is an atomic layer deposition process chamber.

15 4. The system of claim 1, wherein the process chamber is substantially circular, and further comprising a variable gas conductance path that leads to an annular pumping channel surrounding the process chamber.

5. The system of claim 1, wherein the pedestal comprises a chuck assembly for supporting a substrate.

6. The system of claim 5, wherein the chuck assembly comprises an electrostatic chuck.

20 7. The system of claim 1, wherein the pedestal is located at a bottom of the process chamber.

8. The system of claim 1, wherein the chamber lid comprises gas channel openings for feeding gas into the process chamber.

25 9. The system of claim 1 further comprising a variable gas conductance path controlled by a position of the shield.

10. The system of claim 9, wherein the variable gas conductance path is between the shield and the pedestal.

30 11. The system of claim 10, wherein the pedestal is fixed.

12. The system of claim 9 further comprising a pump in communication with the variable gas conductance path for maintaining the process chamber at a subatmospheric pressure during at least a portion of a
35 deposition process.

13. The system of claim 1 comprising a first variable gas conductance path and a second variable conductance path, wherein the first and second variable gas conductance paths are controlled by a position of the shield.

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14. The system of claim 13, wherein the first variable gas conductance path is partially defined by an upper portion of the shield, and the second variable gas conductance path is partially defined by a lower portion of the shield.
- 5 15. The system of claim 1, wherein the shield includes at least one interior cooling channel.
16. The system of claim 1 further comprising a linear motor coupled to the shield for moving the shield.
17. The system of claim 16, wherein the linear motor is coupled to the shield by at least one hollow leg, the
10 hollow leg including a first cooling channel coupled to a second cooling channel in the shield.
18. The system of claim 1 further comprising gas channel openings in the shield for feeding gas into the process chamber.
- 15 19. The system of claim 1 further comprising a chamber body surrounding the process chamber and a substrate entry opening defined in the chamber body, the entry opening allowing placement of a substrate into the process chamber only when the shield is in a first position.
20. A method of modulating a pressure in a processing chamber, the process chamber being defined by a
20 process chamber enclosure, the method comprising the acts of:
 creating a pressure differential between the process chamber and a volume exterior to the process chamber;
 flowing at least one gas between the process chamber and the volume exterior to the process chamber; and
25 varying at least one conductance path of the at least one gas by moving a portion of the process chamber enclosure.
21. The method of claim 20, wherein flowing the at least one gas comprises flowing at least one gas in an atomic layer deposition process.
- 30 22. The method of claim 20, wherein flowing the at least one gas comprises flowing in a cyclic process a first gas followed by a second gas, the second gas being different from the first gas.
23. The method of claim 20, wherein flowing at least one gas comprises flowing the at least one gas
35 through gas channel openings in the portion of the process chamber enclosure.
24. The method of claim 20, wherein the process chamber comprises a chamber top, and, wherein flowing at least one gas comprises flowing the at least one gas through gas channel openings in the chamber top.
- 40 25. The method of claim 20, wherein the portion of the process chamber enclosure forms a lateral wall of the process chamber enclosure.

26. The method of claim 20, wherein the at least one conductance path comprises a first variable gas conductance path and a second variable conductance path.
27. The method of claim 20, wherein varying at least one conductance path comprises moving a shadow ring along with the portion of the process chamber enclosure, the shadow ring surrounding an edge portion of a substrate within the process chamber if the shadow ring is in a first position.
28. The method of claim 27, wherein varying at least one conductance path comprises changing a gap between the shadow ring and the portion of the process chamber enclosure.
29. The method of claim 27, wherein the shadow ring and the portion of the process chamber enclosure form a restricted region, the restricted region forming at least part of the conductance path, and, wherein moving the portion of the process chamber enclosure comprises changing a length of the restricted region.
30. The method of claim 20, wherein moving the portion of the process chamber enclosure comprises changing a gap between the portion of the process chamber enclosure and another part of the process chamber enclosure, the gap forming at least part of the conductance path.
31. The method of claim 20, wherein moving the portion of the process chamber enclosure comprises changing a length of a restricted region between the portion of the process chamber enclosure and another part of the process chamber enclosure, the restricted region forming at least part of the conductance path.
32. The method of claim 20, wherein moving the portion of the process chamber enclosure comprises moving the portion of the process chamber enclosure in a direction perpendicular to a surface of a substrate within the process chamber.
33. The method of claim 20 further comprising using an electrostatic chuck to retain a substrate within the process chamber.
34. The method of claim 33, wherein the chuck is located at a bottom of the process chamber.
35. The method of claim 20 further comprising cooling the portion of the process chamber enclosure by flowing a coolant through at least one cooling channel within the portion of the process chamber enclosure.
36. The method of claim 20 further comprising using a linear motor to move the portion of the process chamber enclosure.
37. The method of claim 20 further comprising introducing a substrate into the process chamber through a substrate entry opening, the entry opening allowing access to the process chamber only when the portion of the process chamber enclosure is in a first position.
38. An atomic layer deposition (ALD) processing system comprising:

- a process chamber for conducting an ALD process;
an electrostatic chuck assembly for retaining a substrate, said chuck assembly comprising at least one chuck electrode, said at least one chuck electrode being biased with a first potential to create electrostatic attraction between said chuck assembly and said substrate to thereby retain said substrate in place on said chuck assembly; and
at least one electrode in said chamber for being coupled to power for creating energetic ions impinging on said substrate, said ions causing a reaction on a surface of said substrate to form a layer on said substrate in an ion induced ALD process.
39. The system of claim 38, wherein said at least one chuck electrode and said at least one electrode are the same.
40. The system of claim 39, wherein said at least one chuck electrode comprises at least a first electrode and a second electrode.
41. The system of claim 40, wherein said first electrode and said second electrode form substantially concentric annular plates.
42. The system of claim 40, wherein said first electrode and said second electrode are interdigitated.
43. The system of claim 40, wherein said first electrode has a D shape and said second electrode has a reverse D shape, with a substantially flat edge of said first electrode facing a substantially flat edge of said second electrode.
44. (Amended) The system of claim 38, wherein said power comprises RF power for creating energetic ions in said chamber.
45. The system of claim 38, wherein said power generates reactive atoms in said chamber.
46. The system of claim 38, wherein said power applied to said at least one electrode controls the energy and density of said ions.
47. The system of claim 38 further comprising a reference electrode in said chamber for use in conjunction with said at least one electrode for creating said plasma.
48. The system of claim 47, wherein said reference electrode comprises a gas inlet for said chamber having at least one opening for gas to enter said chamber, said gas inlet facing a frontside surface of said substrate on which a layer is to be deposited.
49. The system of claim 48, wherein said reference electrode is electrically grounded with respect to a source of said power.

50. The system of claim 48, wherein said gas inlet has an area facing said frontside surface of said substrate, said area being larger than an area of said frontside surface of said substrate.
51. The system of claim 47, wherein said reference electrode is located approximately equal to or less than one inch away from a frontside surface of said substrate on which a layer is to be deposited.
52. The system of claim 47, wherein said reference electrode is located approximately equal to or less than 0.4 inches away from a frontside surface of said substrate on which a layer is to be deposited.
53. The system of claim 47, wherein said reference electrode is located between 0.3 to 0.6 inches away from a frontside surface of said substrate on which a layer is to be deposited.
54. The system of claim 38, wherein said at least one electrode comprises at least one first electrode, said system further comprising at least one second electrode in said chamber coupled to power that is out of phase with said power coupled to said at least one first electrode.
55. The system of claim 54, wherein a magnitude of phase differential between power coupled to said at least one first electrode and said at least one second electrode controls the energy and density of said ions for said ALD process.
56. The system of claim 54, wherein said at least one second electrode comprises a gas inlet for said chamber having openings for gas to enter said chamber.
57. The system of claim 54, wherein said at least one second electrode comprises a gas inlet for said chamber having at least one opening for gas to enter said chamber, said gas inlet facing a frontside surface of said substrate on which a layer is to be deposited.
58. The system of claim 57, wherein said gas inlet has an area facing said frontside surface of said substrate, said area being larger than an area of said frontside surface of said substrate.
59. The system of claim 54, wherein said at least one second electrode is located approximately equal to or less than one inch away from a frontside surface of said substrate on which a layer is to be deposited.
60. The system of claim 54, wherein said at least one second electrode is located approximately equal to or less than 0.4 inches away from a frontside surface of said substrate on which a layer is to be deposited.
61. The system of claim 54, wherein said at least one second electrode is located between 0.3 to 0.6 inches away from a frontside surface of said substrate on which a layer is to be deposited.
62. The system of claim 38, wherein said at least one electrode comprises at least one first electrode, said system further comprising at least one second electrode in said chamber coupled to power that has a frequency different from a frequency of said power coupled to said at least one first electrode.

63. The system of claim 38, wherein said at least one chuck electrode and said at least one electrode are the same and are embedded in said dielectric material, said system further comprising:
a power source coupled to said at least one chuck electrode; and
5 a DC bias source coupled to said at least one chuck electrode.
64. The system of claim 38, wherein a frequency of said power is approximately 13.56 MHz or higher.
65. The system of claim 38, wherein a frequency of said power is approximately 60 MHz.
- 10 66. The system of claim 38, wherein said chuck assembly contacts a backside surface of said substrate, said system further comprising at least one gas inlet opposing said backside surface of said substrate for flowing a backside gas between said substrate and said chuck assembly to enhance thermal communication between said chuck assembly and said substrate.
- 15 67. The system of claim 66, wherein said gas inlet has a plurality of openings.
68. The system of claim 66, wherein said gas inlet has only a single opening.
- 20 69. The system of claim 66, wherein said chuck assembly comprises an annular ring for supporting an edge of said substrate while leaving a gas volume beneath a central portion of said substrate for flowing said backside gas therethrough.
- 25 70. The system of claim 38, wherein said chuck assembly further comprises a gas channel having a plurality of gas openings arranged in a ring to cause a gas output from said gas openings to create a pressure gradient along an edge of said substrate to prevent reactive gases from causing deposition on a backside surface of said substrate.
- 30 71. The system of claim 38, wherein said chuck assembly further comprises a cooling plate, and, wherein flowing a coolant in contact with said cooling plate maintains a desired temperature of said substrate.
- 35 72. The system of claim 71, wherein said cooling plate has an upper surface opposing a first surface of said chuck assembly, said upper surface of said cooling plate being patterned to create one or more thermal breaks between said cooling plate and said first surface of said chuck assembly to increase a temperature difference between said cooling plate and said first surface.
73. The system of claim 38, wherein said power induces a potential on said substrate for attracting and controlling the energy of impinging ions on said substrate.
- 40 74. The system of claim 73, wherein an increase in said power causes an increase in an absolute value of said potential on said substrate.

75. The system of claim 73, wherein said potential is negative.
76. The system of claim 75, wherein said potential is between approximately - 10 volts to -80 volts.
- 5 77. The system of claim 73, wherein said ions have an energy of less than or equal to 150 eV.
78. The system of claim 73, wherein a magnitude of said potential on said substrate is less than or equal to approximately 150 volts.
- 10 79. The system of claim 73, wherein said ions have an energy of between 10 eV to 80 eV.
80. The system of claim 38, wherein said at least one chuck electrode is supported by a dielectric material.
81. The system of claim 38, wherein a magnitude of a potential of said plasma is approximately 10-30
15 volts.
82. The system of claim 38, wherein said chuck assembly further comprises a resistive heater for controlling a temperature of said substrate.
- 20 83. The system of claim 38 further comprising a temperature sensor for controlling cooling and heating of said chuck assembly.
84. The system of claim 38, wherein said power applied to said at least one electrode to create said ions is less than or equal to approximately 150 watts.
- 25 85. The system of claim 38, wherein said power applied to said at least one electrode to create said ions is less than or equal to approximately 1000 watts.
86. The system of claim 38, wherein said power applied to said at least one electrode results in a power
30 density of less than or equal to approximately 3 W/cm².
87. The system of claim 38, wherein said power applied to said at least one electrode results in a power density of less than or equal to approximately 0.5 W/cm².
- 35 88. The system of claim 38 further comprising a reference electrode in said chamber, wherein said reference electrode substantially surrounds a periphery of said substrate.
89. The system of claim 88, wherein said reference electrode has a plurality of openings for providing a gas to said process chamber.
- 40 90. The system of claim 38, wherein said power creates a plasma.

91. The system of claim 38, wherein said surface of said substrate is a surface of a layer that has been deposited on said substrate.

92. The system of claim 38, wherein a distance between said at least one chuck electrode and a backside surface of said substrate and a distance between said at least one RF electrode and said backside surface of said substrate is approximately equal to or less than 2 mm.

93. The system of claim 38, wherein said electrostatic chuck assembly comprises at least a first electrode and a second electrode supported by said dielectric material, said system further comprising:
a DC bias voltage supply coupled across said first electrode and said second electrode to retain said substrate in place by electrostatic attraction; and
a radio frequency (RF) generator coupled to said first electrode and said second electrode for creating a plasma in said process chamber.

94. The system of claim 93 further comprising:
a first RF filter coupled between said first electrode and a first DC potential;
a second RF filter coupled between said second electrode and a second DC potential;
a first DC filter coupled between said first electrode and said RF generator; and
a second DC filter coupled between said second electrode and said RF generator.

95. The system of claim 94, wherein said first RF filter comprises a first inductor, and said second RF filter comprises a second inductor.

96. The system of claim 95, wherein said first RF filter further comprises:
a first capacitor coupled between a first terminal of said first inductor and ground; and
a second capacitor coupled between a second terminal of said first inductor and said ground; and
wherein said second RF filter further comprises:
a third capacitor coupled between a first terminal of said second inductor and said ground; and
a fourth capacitor coupled between a second terminal of said second inductor and said ground.

97. The system of claim 94 further comprising a first load resistor coupled between said first RF filter and said first electrode, and a second load resistor coupled between said second RF filter and said second electrode.

98. The system of claim 94, wherein said first DC filter comprises a capacitor.

99. The system of claim 94, wherein said second DC filter comprises a capacitor.

100. The system of claim 94 further comprising an RF matching circuit coupled between said first DC filter and said RF generator and coupled between said second DC filter and said RF generator.

101. The system of claim 100, wherein said RF matching circuit comprises:

a first variable capacitor including a first terminal coupled to said first DC filter and to said second DC filter;
an inductor including a first terminal coupled to a second terminal of said first variable capacitor,
and a second terminal coupled to said RF generator; and
5 a second variable capacitor including a first terminal coupled to a second terminal of said inductor and to said RF generator, and a second terminal coupled to a ground terminal.

102. The system of claim 100 further comprising a switch, an on state of said switch causing RF power to be coupled to said RF matching circuit.

103. A method performed by an atomic layer deposition (ALD) processing system comprising:
retaining a substrate in an electrostatic chuck assembly within a process chamber, said chuck
assembly comprising at least one chuck electrode supported by a dielectric material, said at least
one chuck electrode being biased with a first potential to create electrostatic attraction between
15 said chuck assembly and said substrate to thereby retain said substrate in place on said chuck;
and
applying to at least one electrode power for creating energetic ions impinging on said substrate to
cause a reaction on a surface of said substrate to form a layer on said substrate in an ion induced
ALD process.

104. The method of claim 103, wherein said at least one chuck electrode and said at least one electrode are the same.

105. The method of claim 103, wherein said power comprises RF power generating energetic ions in said
25 chamber to perform said ALD process.

106. The method of claim 103, wherein said power generates reactive atoms in said chamber to perform said ALD process.

107. The method of claim 103, wherein said power creates a plasma.

108. The method of claim 103 further comprising:
applying a first DC potential to a first electrode in said electrostatic chuck assembly and applying a
second DC potential to a second electrode in said chuck assembly to create said electrostatic
35 attraction to said substrate for retaining said substrate on said chuck assembly;
grounding an electrode in said process chamber;
flowing at least one gas into said process chamber; and
applying power to said first electrode and said second electrode to create said energetic ions.

109. The method of claim 103, wherein said energetic ions are created by increasing a pressure of said at
40 least one gas in said chamber until a plasma ignites.

110. The method of claim 103, wherein said applying said power comprises closing a switch coupled to a generator to ignite a plasma.
111. The method of claim 103 further comprising terminating a generated plasma by opening a switch.
- 5 112. The method of claim 103 further comprising terminating a generated plasma by lowering a gas pressure in said chamber.
- 10 113. The method of claim 103, wherein applying said power to create said energetic ions comprises applying power of approximately equal to or less than 150 watts.
114. The method of claim 103, wherein said power is at a frequency of approximately 13.56 MHz or higher.
- 15 115. The method of claim 103, wherein said power induces a potential on said substrate for attracting and controlling the energy of impinging ions on said substrate.
116. The method of claim 115, wherein an increase in said power causes an increase in an absolute value of said potential on said substrate.
- 20 117. The method of claim 115, wherein said potential is negative.
118. The method of claim 115, wherein said potential is between approximately -10 volts to -80 volts.
- 25 119. The method of claim 115, wherein said ions have an energy of less than or equal to 150 eV.
120. The method of claim 115, wherein a magnitude of said potential on said substrate is less than or equal to approximately 150 volts.
- 30 121. The method of claim 115, wherein said ions have an energy of between 10 eV to 80 eV.
122. The method of claim 103, wherein said power applied to said at least one electrode results in a power density of less than or equal to approximately 3 W/cm².
- 35 123. The method of claim 103, wherein said power applied to said at least one electrode results in a power density of less than or equal to approximately 0.5 W/cm².
124. The method of claim 103, wherein said flowing said at least one gas comprises injecting gas into said process chamber through a grounded electrode.
- 40 125. The method of claim 124, wherein said grounded electrode is located to oppose a frontside surface of said substrate.

126. The method of claim 124, wherein said grounded electrode substantially surrounds a periphery of said substrate.

5 127. The method of claim 103, wherein said method forms a metal-containing layer on said substrate in said ALD process.

128. A system for controlling the temperature of a substrate in an atomic layer deposition (ALD) process chamber comprising:

10 an electrostatic chuck assembly for retaining a substrate on said chuck assembly by electrostatic attraction, said substrate, when retained by said chuck assembly, forming a backside gas volume bounded by a backside surface of said substrate; and
a gas inlet leading to said backside gas volume for supplying a backside gas to said backside gas volume for providing a thermal transfer between said chuck assembly and said backside surface
15 of said substrate during said ALD process.

129. The system of claim 128, wherein said gas inlet has a plurality of openings.

130. The system of claim 128, wherein said gas inlet has only a single opening.

20 131. The system of claim 128, wherein said chuck assembly comprises an annular ring for supporting an edge of said substrate while leaving said gas volume beneath a central portion of said substrate for flowing said backside gas therethrough.

25 132. The system of claim 128, wherein said chuck assembly further comprises a gas channel having a plurality of gas openings arranged in a ring to cause a gas output from said gas openings to create a pressure gradient along an edge of said substrate to reduce the partial pressure of reactive gasses along said edge and to prevent reactive gases from causing deposition on a backside surface of said substrate or deposition on a surface or edge of said chuck assembly.

30 133. The system of claim 128 further comprising:
at least one coolant channel for flowing a coolant therethrough for cooling said chuck assembly;
a heater for heating said substrate;
a temperature sensor for detecting a temperature corresponding to a temperature of said substrate;
35 and
at least one controller controlling said heater, said coolant, and said backside gas to regulate a temperature of said substrate.

40 134. The system of claim 133, wherein said at least one controller comprises a gas pressure controller for regulating said backside gas.

135. The system of claim 133, wherein said temperature sensor is part of said chuck assembly.

136. The system of claim 133, wherein said temperature sensor is an optical sensor.
137. The system of claim 136, wherein said temperature sensor optically measures a temperature of said
5 backside surface of said substrate.
138. The system of claim 133, wherein said temperature sensor is a thermocouple that measures a temperature of said chuck assembly.
- 10 139. The system of claim 133, wherein said at least one controller comprises a flow controller for controlling a flow of said coolant through said coolant channel.
140. The system of claim 133, wherein said heater comprises a resistive heater formed as part of said
15 chuck assembly.
141. The system of claim 133, wherein said heater is external to said chuck assembly.
142. The system of claim 141, wherein said heater comprises one or more lamps.
- 20 143. The system of claim 141, wherein said heater comprises a plasma.
144. The system of claim 133, wherein said at least one controller controls any combination of said heater, said coolant, and said backside gas to regulate a temperature of said substrate.
- 25 145. The system of claim 128, wherein said chuck assembly further comprises a cooling plate, and, wherein flowing said coolant in contact with said cooling plate maintains a desired temperature of said substrate.
146. The system of claim 128 further comprising a thermal break between said chuck assembly and other
30 portions of said process chamber to reduce thermal communication between said chuck assembly and said other portions.
147. The system of claim 128 further comprising at least one gas inlet for supplying at least one gas into said process chamber for reacting with a frontside surface of said substrate in said atomic layer deposition
35 process to form a layer on said frontside surface.
148. The system of claim 128, wherein said backside gas includes one of argon, helium, and hydrogen.
149. The system of claim 128, wherein said backside gas provides a backside gas pressure between 3–20
40 torr.

150. The system of claim 128, wherein said backside gas provides a backside gas pressure between 6–10 torr.

151. A method for controlling the temperature of a substrate in an atomic layer deposition (ALD) process chamber comprising:

5 retaining a substrate on an electrostatic chuck assembly by electrostatic attraction, said substrate, when retained by said chuck assembly, forming a backside gas volume bounded by a backside surface of said substrate; and
10 providing a backside gas for flowing through said backside gas volume, said backside gas providing a thermal transfer between said chuck assembly and said backside surface of said substrate.

152. The method of claim 151 further comprising supplying at least one gas into said process chamber for reacting with a frontside surface of said substrate in said atomic layer deposition process to form a layer on said frontside surface.

153. The method of claim 151, wherein said chuck assembly further comprises a gas channel having a plurality of gas openings arranged in a ring, said method further comprising outputting a gas from said gas openings to create a pressure gradient along an edge of said substrate to reduce the partial pressure of reactive gases along said edge and to prevent reactive gases from causing deposition on a backside surface of said substrate or deposition on a surface or edge of said chuck assembly.

154. The method of claim 151 further comprising:
25 detecting a temperature corresponding to a temperature of said substrate; and controlling a chuck assembly heater, controlling coolant flowing through a coolant channel thermally coupled to said chuck assembly, and controlling said backside gas to regulate a temperature of said substrate.

155. The method of claim 154, wherein said detecting said temperature is performed by optically measuring a temperature of said backside surface of said substrate.

156. The method of claim 154, wherein said detecting said temperature is performed by a thermocouple that measures a temperature of said chuck assembly.

157. The method of claim 154, wherein said controlling said chuck assembly heater comprises controlling a resistive heater formed as part of said chuck assembly.

158. The method of claim 154, wherein said controlling said chuck assembly heater comprises controlling a plasma.

40 159. The method of claim 151, wherein said backside gas includes one of argon, helium, and hydrogen.

160. The method of claim 151, wherein said backside gas provides a backside gas pressure between 3–20 torr.
161. The method of claim 151, wherein said backside gas provides a backside gas pressure between 6–10 torr.
162. A thin film deposition method comprising the acts of:
introducing a first gas into a deposition chamber for reacting with a surface of a substrate in the chamber to form a layer over the substrate;
detecting a change in pressure of the first gas in the chamber; and
automatically introducing a second gas into the chamber in response to the detection of the change in pressure.
163. The method of claim 162, wherein the layer is formed directly on the substrate.
164. The method of claim 162, wherein introducing the first gas comprises introducing a precursor, and, wherein introducing the second gas comprises using the second gas to purge the first gas from the chamber.
165. The method of claim 164, wherein the precursor forms a monolayer over the substrate.
166. The method of claim 164, wherein the precursor reacts with a monolayer previously formed over the substrate to form the thin film.
167. The method of claim 162, wherein introducing the first gas comprises using the first gas to purge a third gas from the chamber, and, wherein introducing the second gas comprises introducing a precursor.
168. The method of claim 167, wherein the precursor forms a monolayer over the substrate.
169. The method of claim 167, wherein the precursor reacts with a monolayer previously formed over the substrate to form the thin film.
170. The method of claim 162, wherein introducing the second gas comprises using a single valve to stop the introduction of the first gas and to introduce the second gas.
171. The method of claim 162, wherein detecting the change in pressure comprises detecting a pressure reduction.
172. The method of claim 162 further comprising the act of changing a pressure in the chamber by changing a conductance of a gas exit path from the chamber.

173. The method of claim 172, wherein changing the conductance comprises changing a cross-sectional area of the exit path, changing a length of the exit path, or changing both the cross-sectional area and length of the exit path.

5 174. The method of claim 172, wherein changing the pressure comprises moving a shield substantially surrounding the substrate.

175. The method of claim 162, wherein detecting the change in pressure comprises detecting an output of a pressure switch mounted within the chamber.

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176. The method of claim 162, wherein the change in pressure is a decrease caused by increasing a conductance of a gas exit path from the chamber; and further comprising activating at least one valve to introduce the second gas into the chamber and to block the first gas from entering the chamber.

15 177. The method of claim 162 further comprising the acts of:
decreasing a flux of the second gas in the chamber by increasing the conductance of a gas exit path from the chamber;
detecting a pressure decrease of the second gas; and
introducing the first gas into the chamber in response to detecting the pressure decrease of the
20 second gas.

178. The method of claim 162 further comprising the act of creating a plasma in the second gas to react with the layer.

25 179. The method of claim 178, wherein the plasma is ignited by raising the pressure of the second gas in the chamber.

180. The method of claim 178, wherein the plasma is ignited by applying RF power to the second gas.

30 181. The method of claim 178 further comprising terminating the plasma by lowering the pressure of the second gas in the chamber.

182. The method of claim 178 further comprising terminating the plasma by removing RF power from the second gas.

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183. The method of claim 162, wherein the thin film comprises a metal.

184. The method of claim 162 further comprising the act of using the second gas to purge the first gas from the chamber.

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185. The method of claim 162, wherein the second gas reacts with the layer to form the thin film.

186. The method of claim 162 further comprising the act of promoting a reaction between the layer and the second gas by increasing the pressure of the second gas in the chamber.

187. A thin film deposition apparatus comprising:

- 5 a thin film deposition chamber;
 a sensor for sensing pressure in the chamber; and
 a controller coupled to the sensor and for controlling introduction of a first and a second gas into the chamber, wherein if the sensor detects a decrease of the pressure of the first gas in the chamber, the controller automatically introduces the second gas into the chamber.

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188. The apparatus of claim 187 further comprising a restriction defining a gas exit path from the chamber, wherein a variable conductance is defined for the restriction.

15

189. The apparatus of claim 188, wherein the restriction comprises a gap between a support for a substrate and a movable shield around the support.

190. An atomic layer deposition method comprising the acts of:

- supplying a first gas to a process chamber, wherein the first gas comprises a first reactant to react with a surface of a substrate in the process chamber to form a first layer;
20 using a second gas to purge the first gas from the chamber; and
 subsequent to the purge, using a second reactant from the second gas to react with the first layer to form a second layer.

25

191. The method of claim 190, wherein the reaction to form the first layer comprises chemisorption.

192. The method of claim 190, wherein the first reactant comprises titanium, tungsten, tantalum, or copper.

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193. The method of claim 190 further comprising the act of applying an electrical bias to the substrate to attract charged components of the first gas towards the substrate to promote a reaction of the first reactant with the substrate.

194. The method of claim 193, wherein the electrical bias is DC.

35

195. The method of claim 193, wherein the bias orients the first reactant with respect to the substrate.

196. The method of claim 195, wherein the magnitude of the bias is a minimum required to impart on the first reactant a moment for correct orientation with respect to the substrate.

40

197. The method of claim 190, wherein the acts of supplying the first gas, using the second gas to purge the first gas, and using the second reactant from the second gas to react with the first layer are repeated to deposit a film of a desired thickness.

198. The method of claim 190 further comprising the act of inserting a delay between the acts of supplying the first gas and using the second gas to purge the first gas.

199. The method of claim 198, wherein the delay is sufficient to prevent a reaction between the first gas and the second gas.

200. The method of claim 190 comprising the act of creating a plasma in the chamber to produce the second reactant.

201. The method of claim 200 further comprising the act of controlling the creation of the plasma by varying a pressure of the second gas in the chamber.

202. The method of claim 200 further comprising the act of using RF power to control ignition and termination of the plasma.

203. The method of claim 190, wherein the reaction to form the second layer comprises a self-limiting reaction that halts once substantially all of the first layer reacts with the second reactant.

204. The method of claim 190 further comprising the act of maintaining a temperature of the substrate at a temperature low enough to avoid decomposition of the first reactant and the second reactant.

205. The method of claim 190, wherein the second reactant comprises hydrogen.

206. The method of claim 190, wherein the second gas comprises argon, helium, hydrogen, or mixtures thereof.

207. The method of claim 200, wherein the plasma comprises energetic ions.

208. The method of claim 207, wherein the energetic ions comprise argon or helium ions.

209. The method of claim 200, wherein the plasma comprises reactive atoms.

210. The method of claim 209, wherein the reactive atoms comprise hydrogen.

211. The method of claim 200, wherein the plasma comprises energetic ions, and further comprising the act of using the energetic ions to drive the reaction to form the second layer.

212. The method of claim 190, wherein the first gas comprises t-butylimino tris(diethylamino)tantalum (TBTDET), (trimethylvinylsilyl)hexafluoroacetylacetonato copper I (Cupraselect®), pentakis(diethylamido)tantalum (PDEAT), pentakis(ethylmethylamido)tantalum (PEMAT), tetrakis(dimethylamido)titanium (TDMAT), tetrakis(diethylamino)titanium (TDEAT), CuCl, TaBr₅, TaCl₅, TiCl₄, W(CO)₆, or WF₆.

213. The method of claim 190, wherein the second gas does not cause gas phase reactions with the first gas.
- 5 214. The method of claim 190, wherein the first gas comprises a single type of gas.
215. The method of claim 190, wherein the second gas comprises a single type of gas.
216. An atomic layer deposition method comprising the acts of:
- 10 providing a first gas in a process chamber, wherein the first gas comprises a first reactant to react with a surface of a substrate in the process chamber to form a first layer;
- providing a second gas to the process chamber, wherein the second gas comprises a second reactant and ions; and
- 15 using the ions to drive a reaction between the second reactant and the first layer to form a second layer.
217. The method of claim 216 further comprising the act of electrically biasing the substrate to orient the first reactant with reference to the substrate.
- 20 218. The method of claim 217, wherein biasing the substrate comprises using a minimum bias required to impart on the first reactant a moment for correct orientation with respect to the substrate.
219. The method of claim 216, wherein providing the second gas in the process chamber comprises using the second gas to purge the first gas from the process chamber.
- 25 220. The method of claim 216, wherein using the ions comprises electrically biasing the substrate.
221. The method of claim 216 further comprising the act of creating a plasma to generate the second reactant and ions.
- 30 222. An atomic layer deposition process comprising the acts of:
- providing a precursor gas in a process chamber for reacting with a surface of a substrate in the chamber;
- inducing a voltage on the substrate; and
- 35 using the induced voltage to promote a reaction between the precursor and the surface of the substrate.
223. The method of claim 222, wherein the induced voltage comprises a continuous DC bias voltage.
- 40 224. The method of claim 222, wherein inducing the voltage comprises applying a DC reference voltage to an electrostatic chuck supporting the substrate.

225. The method of claim 224, wherein the application of the DC reference voltage is exclusive of an application of RF power to the precursor gas.
226. The method of claim 222, wherein inducing the voltage comprises application of a DC reference voltage to an electrode positioned on a side of the substrate opposite from the precursor gas.
227. The method of claim 226, wherein the electrode comprises an annular shape, a D-shape, or a shape interdigitated with another electrode.
228. The method of claim 226, wherein the application of the DC reference voltage is exclusive of application of RF power to the precursor gas.
229. The method of claim 222, wherein the induced voltage imparts a moment on a reactant in the precursor gas, the moment being sufficient to align the reactant for the reaction with the surface of the substrate.
230. The method of claim 229, wherein the induced voltage is a minimum magnitude required to impart the moment.
231. The method of claim 222, wherein the reaction comprises chemisorption.
232. The method of claim 222, wherein the induced voltage is less than 50 V.
233. The method of claim 222, wherein the induced voltage is an opposite polarity from a charge of ligands in the precursor gas.
234. The method of claim 222, wherein the precursor gas comprises t-butylimino tris(diethylamino)tantalum (TBTDET), and the polarity of the induced voltage is positive.
235. The method of claim 222, wherein the precursor gas comprises (trimethylvinylsilyl)hexafluoroacetylacetonato copper I (Cupraselect®) or t-butylimino tris(diethylamino)tantalum (TBTDET), and the polarity of the induced voltage is negative.
236. The method of claim 222, wherein the precursor gas comprises pentakis(diethylamido)tantalum (PDEAT), pentakis(ethylmethylamido)tantalum (PEMAT), tetrakis(diethylamino)titanium (TDEAT), tetrakis(dimethylamido)titanium (TDMAT), TaBr₅, TaCl₅, TiCl₄, CuCl, W(CO)₆, or WF₆, and the polarity of the induced voltage is opposite to a charge of the precursor.
237. An atomic layer deposition apparatus comprising:
a process chamber for receiving a precursor gas for reacting with a surface of a substrate in the chamber; and

a DC reference voltage source coupled to induce a voltage on the substrate to promote a reaction between the precursor and the surface of the substrate.

238. The apparatus of claim 237 further comprising an electrostatic chuck supporting the substrate,
5 wherein an electrode in the chuck is coupled to the DC reference voltage source.

239. The apparatus of claim 237 further comprising an RF power source coupled to provide RF power to the gas.

10 240. The apparatus of claim 239 further comprising at least one switch coupled to allow the DC reference voltage source to be coupled to induce the voltage on the substrate and to prevent the RF power source from being coupled to provide RF power to the gas.

241. The apparatus of claim 237 further comprising an electrode positioned on a side of the substrate
15 opposite from the precursor gas, wherein the electrode is coupled to the DC reference voltage source.

242. The apparatus of claim 241, wherein the electrode comprises an annular shape, a D-shape, or a shape interdigitated with another electrode.

20 243. The apparatus of claim 241 further comprising an RF power source coupled to provide RF power to the electrode.

244. The apparatus of claim 243 further comprising at least one switch coupled to allow the DC reference voltage source to be coupled to the electrode and to prevent the RF power source from being coupled to the
25 electrode.

245. The apparatus of claim 237, wherein the induced voltage imparts a moment on a reactant in the precursor gas, the moment being sufficient to align the reactant for the reaction with the surface of the
30 substrate.

246. The apparatus of claim 245, wherein the induced voltage is a minimum magnitude required to impart the moment.

247. The apparatus of claim 237, wherein the reaction comprises chemisorption.
35

248. The apparatus of claim 237, wherein the induced voltage is less than 50 V.

249. The apparatus of claim 237, wherein a polarity of the induced voltage is of opposite polarity to the charge of ligands in the precursor gas.

40 250. The apparatus of claim 237, wherein the precursor gas comprises t-butylimino tris(diethylamino)tantalum (TBTDET), and the polarity of the voltage is positive.

251. The apparatus of claim 237, wherein the precursor gas comprises (trimethylvinylsilyl)hexafluoroacetylacetonato copper I (Cupraselect®), and the polarity of the induced voltage is negative.

5

252. The apparatus of claim 237, wherein the precursor gas comprises pentakis(diethylamido)tantalum (PDEAT), pentakis(ethylmethyldamido)tantalum (PEMAT), tetrakis(diethylamino)titanium (TDEAT), tetrakis(dimethylamido)titanium (TDMAT), TaBr₅, TaCl₅, TiCl₄, CuCl, W(CO)₆, or WF₆, and the polarity of the induced voltage is opposite to a charge of the precursor.

10

253. The apparatus of claim 237 further comprising first and second electrodes positioned on a side of the substrate opposite from the precursor gas, and, wherein the DC reference voltage source comprises a first voltage supply coupled to the first electrode and a second voltage supply coupled to the second electrode.

15

254. The apparatus of claim 253 further comprising an RF power source coupled to the first electrode.

255. An atomic layer deposition (ALD) processing system comprising:
a process chamber; and
an N-way valve structure coupling gases to said process chamber.

20

256. A system comprising:
a deposition process chamber defined at least in part by a top, a bottom, and a peripheral wall; and
a plurality of orifices in the wall, wherein the orifices are positioned to introduce a gas into the chamber in a plane substantially parallel to a deposition side of a substrate positioned in the chamber.

25

257. The system of claim 256, wherein the bottom comprises a support structure on which the substrate is positioned during a deposition process, and, wherein the support structure comprises at least one orifice for introducing gas near the wall.

30

258. The system of claim 257, wherein the at least one orifice in the support structure is positioned outside a periphery of the positioned substrate.

259. The system of claim 257, wherein the at least one orifice in the support structure is positioned inside a periphery of the positioned substrate.

35

260. The system of claim 257, wherein the bottom comprises a support structure on which the substrate is positioned during a deposition process, and, wherein the support structure comprises a plurality of orifices positioned near a periphery of the positioned substrate.

40

261. The system of claim 260, wherein the plurality of orifices in the support structure are positioned outside the periphery of the positioned substrate.

262. The system of claim 260, wherein the plurality of orifices in the support structure are positioned inside the periphery of the positioned substrate.
- 5 263. The system of claim 256, wherein the bottom comprises a support structure on which the substrate is positioned during a deposition process, and, wherein the support structure comprises at least one orifice positioned to ensure a constant pressure gradient at a periphery of the positioned substrate.
- 10 264. The system of claim 256, wherein the wall is sized such that the orifices introduce the gas close to a peripheral edge of the substrate.
265. The system of claim 256, wherein:
the bottom comprises a pedestal over which the substrate is positioned;
the top comprises a chamber lid offset in a particular dimension from the pedestal; and
15 the wall comprises a movable shield surrounding at least a portion of the pedestal and at least a portion of the lid, wherein the shield moves back and forth around the chamber lid and the pedestal in the particular dimension.
- 20 266. The system of claim 256 further comprising a gap defined between the bottom and the peripheral wall, wherein the gap surrounds the substrate positioned in the chamber.
267. The system of claim 266, wherein the gap comprises a variable gas flow restriction.
268. The system of claim 267, wherein the restriction is made variable by movement of the wall.
- 25 269. The system of claim 266, wherein the gap comprises an annular shape.
270. The system of claim 256 further comprising a gap defined between the top and the peripheral wall.
- 30 271. The system of claim 270, wherein the gap comprises a variable gas flow restriction.
272. The system of claim 271, wherein the restriction is made variable by movement of the wall.
273. The system of claim 270, wherein the gap comprises an annular shape.
- 35 274. The system of claim 256 further comprising:
a first gap defined between the bottom and the peripheral wall; and
a second gap defined between the bottom and the peripheral wall;
wherein the first gap surrounds the substrate positioned in the chamber.
- 40 275. The system of claim 274, wherein the first and second gaps comprise variable gas flow restrictions.

276. The system of claim 275, wherein the restrictions are made variable by movement of the wall.

277. The system of claim 274, wherein the first and second gaps each comprise an annular shape.

5 278. A method comprising the acts of:

positioning into a deposition chamber a substrate comprising a deposition side; and
introducing gas into the chamber in a substantially symmetric geometry inwards towards a center of
the deposition side, wherein the gas introduction is in a plane substantially parallel to the
deposition side.

10

279. The method of claim 278 further comprising the act of introducing gas through a support structure on
which the substrate is positioned, wherein introducing gas through the support structure occurs near a
peripheral wall of the chamber.

15 280. The method of claim 279, wherein introducing gas through the support structure comprises
introducing gas through at least one orifice positioned near a periphery of the substrate.

281. The method of claim 280, wherein the or each orifice is positioned outside the periphery of the
substrate.

20

282. The method of claim 280, wherein the or each orifice is positioned inside the periphery of the
substrate.

283. The method of claim 279, wherein gas introduced in the plane substantially parallel to the deposition
25 side and gas introduced through the support structure is the same type of gas.

284. The method of claim 278, wherein introducing gas comprises introducing gas near a periphery of the
substrate.

30 285. The method of claim 278, wherein introducing gas comprises introducing gas through a plurality of
orifices positioned in a peripheral wall of the deposition chamber.

286. The method of claim 278, wherein introducing gas comprises introducing gas through a single, unique
orifice positioned in a peripheral wall of the deposition chamber.

35

287. The method of claim 278 further comprising the act of moving the plane of gas introduction in a
direction substantially perpendicular to the deposition side.

288. The method of claim 278 further comprising the act of controlling a flow of gas through the chamber
40 by varying a flow restriction through which gas exits the chamber.

289. The method of claim 288, wherein the restriction surrounds the substrate.

290. The method of claim 278 further comprising the act of controlling a pressure of gas in the chamber by varying a flow restriction through which gas exits the chamber.

5 291. The method of claim 290, wherein the restriction surrounds the substrate.

292. The method of claim 278 further comprising the act of introducing gas into the chamber through a top of the chamber and in a direction substantially perpendicular to the deposition side.

10 293. The method of claim 292, wherein gas introduced in the plane substantially parallel to the deposition side and gas introduced substantially perpendicular to the deposition side is the same type of gas.

294. The method of claim 292 further comprising the act of moving the plane of parallel gas introduction in a direction substantially perpendicular to the deposition side.

15

295. The method of claim 292 further comprising the act of controlling a flow of gas through the chamber by varying a flow restriction through which gas exits the chamber.

296. The method of claim 292, wherein the restriction surrounds the substrate.

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297. The method of claim 292 further comprising the act of controlling a pressure of gas in the chamber by varying a flow restriction through which gas exits the chamber.

298. The method of claim 297, wherein the restriction surrounds the substrate.

25

299. The method of claim 292 further comprising the act of controlling a flux of gas in the chamber by varying a flow restriction through which gas exits the chamber.

300. The method of claim 299, wherein the restriction surrounds the substrate.

30

301. The method of claim 292, wherein the parallel and perpendicular gas introduction is simultaneous.

302. A method comprising the acts of:

35 supplying an atomic layer deposition process gas to a process chamber, wherein a gas flow conductance is defined for gas exiting the chamber; and
varying a flux of the deposition process gas to a substrate in the process chamber by varying the conductance;
wherein varying the conductance comprises varying a restriction through which gas exits the chamber.

40

303. The method of claim 302 further comprising the act of maintaining a substantially constant flow rate of the gas into the chamber while varying the conductance.

304. The method of claim 302, wherein varying the conductance varies a flux of ions to the substrate.
305. The method of claim 302, wherein varying the conductance varies a flux of reactive atoms to the
5 substrate.
306. The method of claim 302, wherein the flux of the gas on the substrate varies inversely with the conductance.
- 10 307. The method of claim 302, wherein a pressure in the process chamber varies inversely with the chamber conductance.
308. The method of claim 302, wherein varying the conductance comprises alternating the conductance between a first conductance and a second conductance, the second conductance being higher than the first
15 conductance.
309. The method of claim 308, wherein the alternating between the first and second conductances is periodic.
- 20 310. The method of claim 308 further comprising the act of generating ions during first conductance periods.
311. The method of claim 308 further comprising the act of generating reactive atoms during first conductance periods.
25
312. The method of claim 308 further comprising the act of generating a plasma during first conductance periods.
313. The method of claim 312, wherein generating the plasma comprises applying RF power within the
30 process chamber during first conductance periods.
314. The method of claim 312, wherein generating the plasma comprises applying constant RF power within the process chamber, and further comprising the acts of:
igniting the plasma by increasing chamber pressure by lowering the conductance; and
35 extinguishing the plasma by decreasing chamber pressure by increasing the conductance.
315. The method of claim 302, wherein said varying a flux is part of a deposition sequence, the deposition sequence comprising separating each of a plurality of low conductance periods from one another by one of a plurality of high conductance periods.
40
316. The method of claim 302, wherein the deposition process gas is a first deposition process gas, and further comprising the acts of:

using the first deposition process gas to form a monolayer on a surface of the substrate;
removing the first deposition process gas from the chamber;
introducing a second atomic layer deposition process gas to the process chamber;
generating ions from the second deposition process gas by igniting a plasma;
5 using the ions to promote a reaction between the second deposition process gas and the monolayer;
and
removing the second deposition process gas;
wherein varying the conductance comprises increasing the conductance during the removing of the
first deposition process gas, decreasing the conductance during the introduction of the second
10 deposition process gas, and increasing the conductance during the removing of the second
deposition process gas.

317. The method of claim 302, wherein the deposition process gas is a first deposition process gas, and
further comprising the acts of:
15 using the first deposition process gas to form a monolayer on a surface of the substrate;
removing the first deposition process gas from the chamber;
introducing a second atomic layer deposition process gas to the process chamber;
generating reactive atoms from the second deposition process gas by igniting a plasma;
reacting the reactive atoms with the monolayer to form a thin film; and
20 removing the second deposition process gas;
wherein varying the conductance comprises increasing the conductance during the removing of the
deposition process gas, decreasing the conductance during the introduction of the second
deposition process gas, and increasing the conductance during the removing of the second
deposition process gas.

25 318. The method of claim 302 further comprising the act of introducing purge gas pulses to the process
chamber.

319. The method of claim 318, wherein varying the conductance comprises varying the conductance
30 between a first conductance and a second conductance, the second conductance being higher than the first
conductance, wherein second conductance periods occur at the beginning and end of each purge gas pulse
and a period of first conductance occurs between the second conductance periods.

320. A method comprising the acts of:
35 establishing a first flux of a first atomic layer deposition process gas over a substrate positioned in a
process chamber by setting a first conductance of the chamber as the first process gas deposits a
monolayer over a surface the substrate;
establishing a second flux of the first process gas over the substrate by setting a second conductance
of the chamber, higher than the first conductance, as the first process gas is removed from the
40 chamber;

establishing a first flux of a second atomic layer deposition process gas over the substrate by setting a third conductance of the chamber as the second process gas reacts with the deposited monolayer; and

5 establishing a second flux of the second process gas over the substrate by setting a fourth conductance of the chamber, higher than the third conductance, as the second process gas is removed from the chamber.

321. A method comprising the acts of:

10 supplying an atomic layer deposition process gas to a process chamber, wherein a gas flow conductance is defined for gas exiting the chamber; and
varying a flux of the deposition process gas to a substrate in the process chamber by varying the conductance;
wherein varying the conductance comprises moving a shield defining a periphery of the chamber.

15

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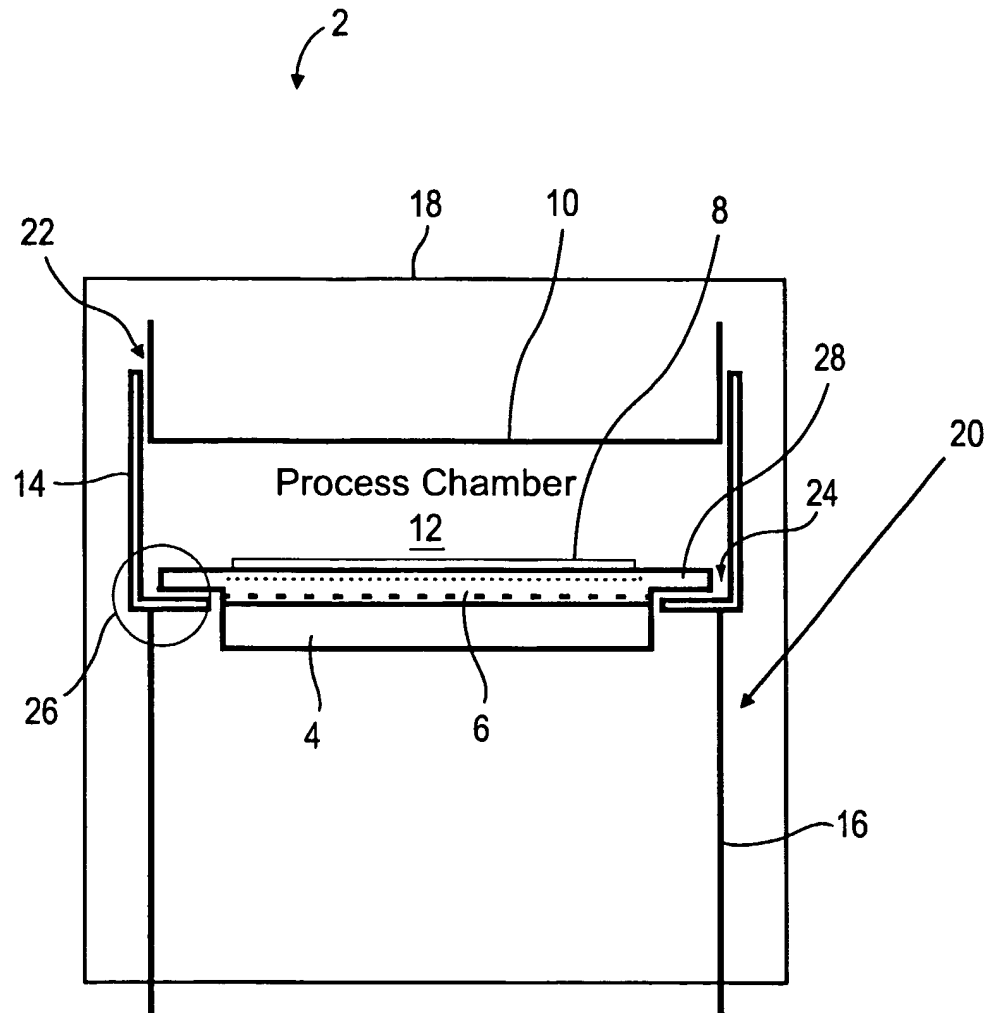


FIG. 1

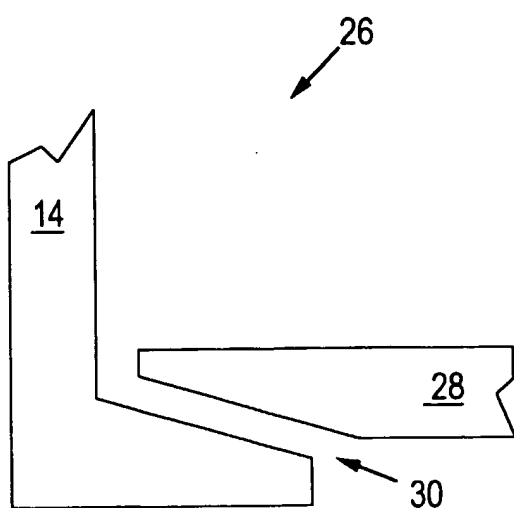


FIG. 2(a)

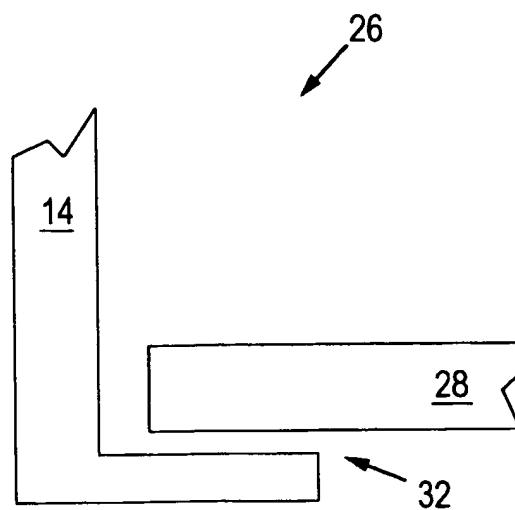


FIG. 2(b)

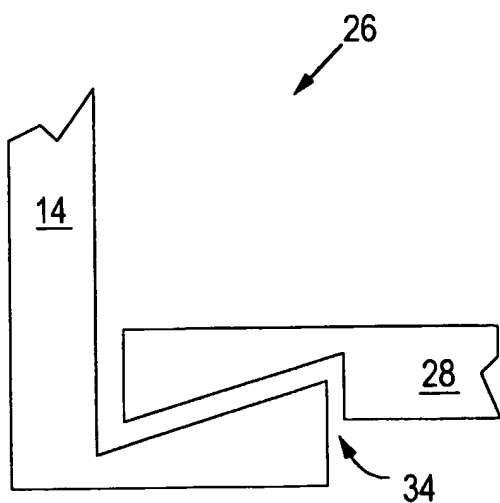


FIG. 2(c)

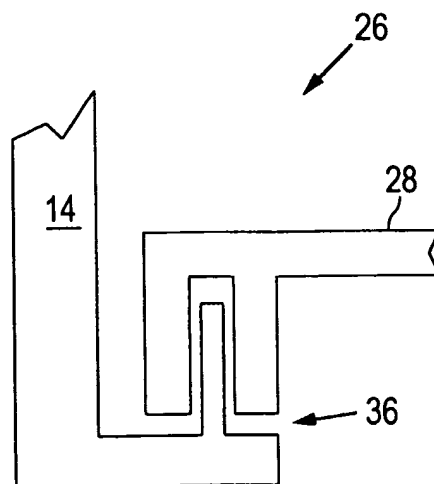


FIG. 2(d)

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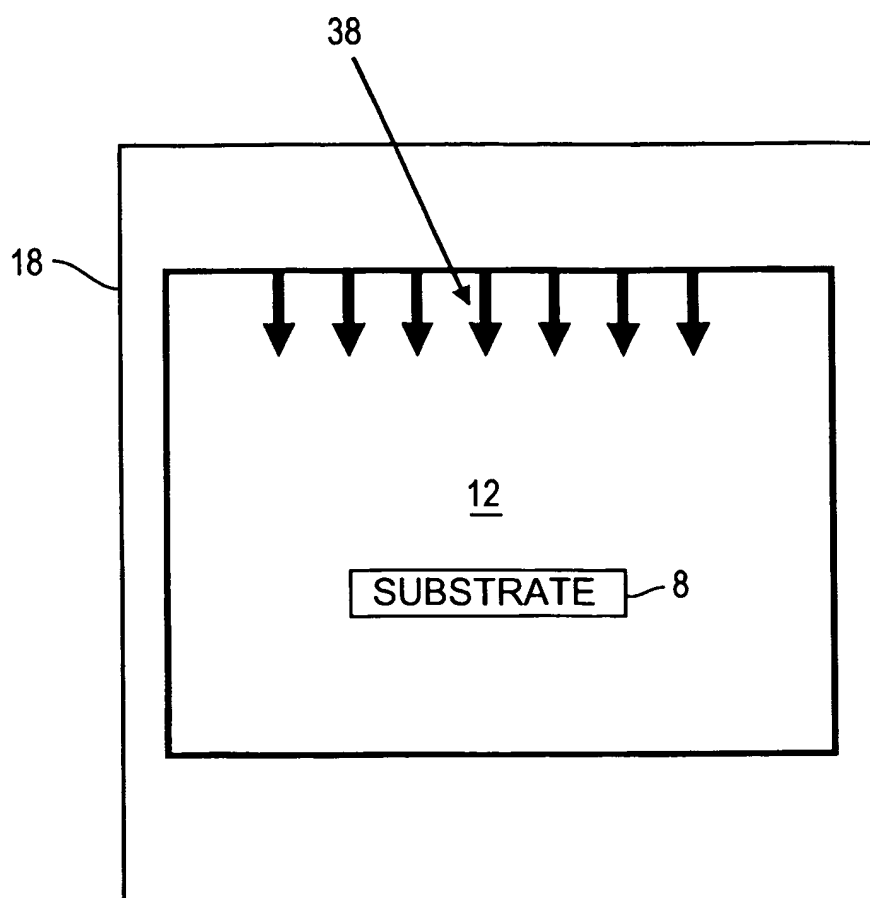


FIG. 3

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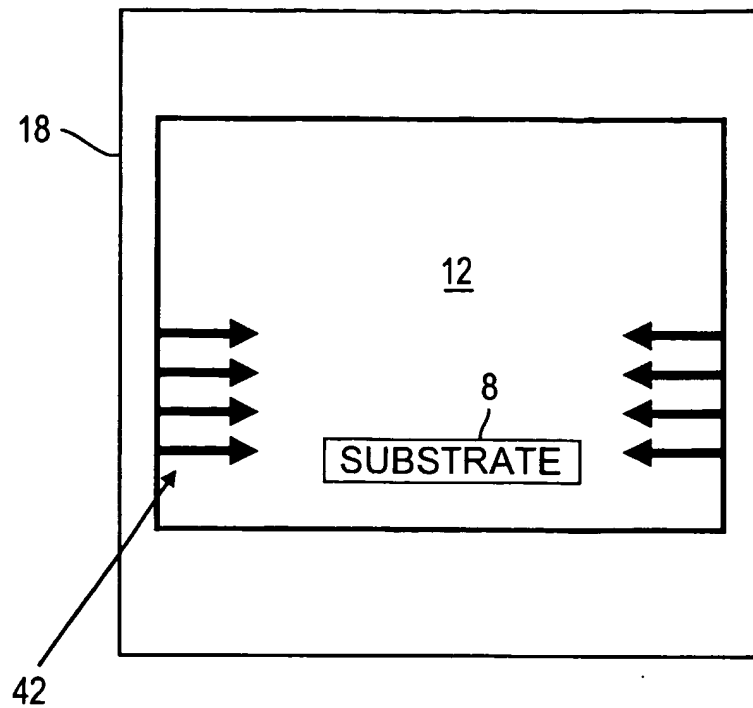


FIG. 4(a)

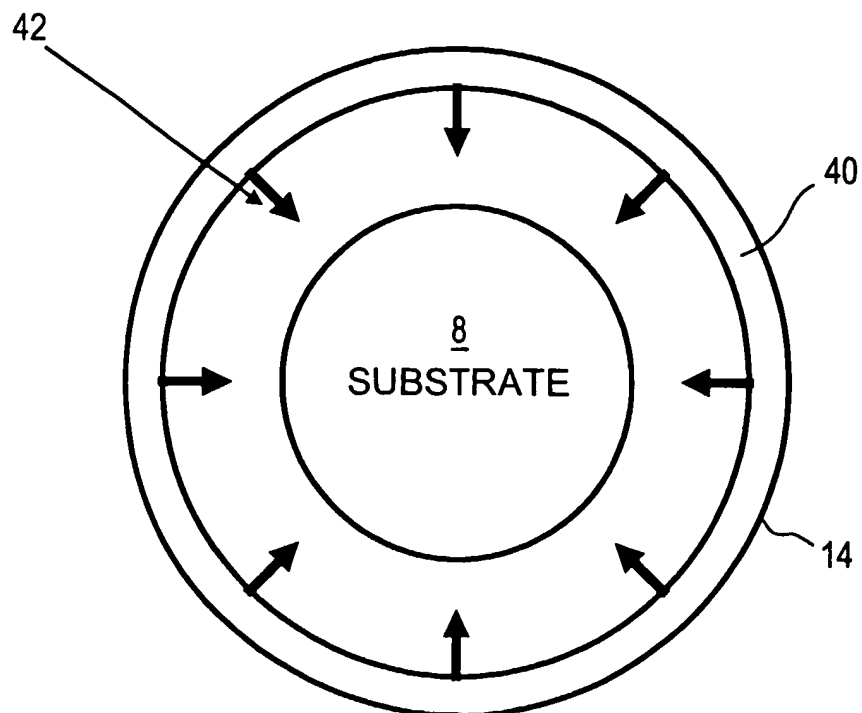


FIG. 4(b)

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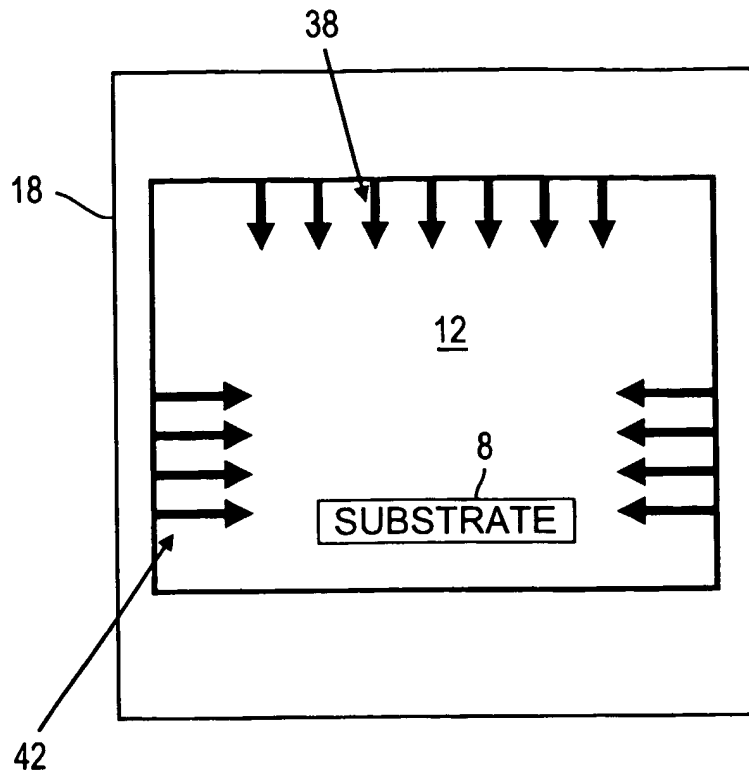


FIG. 5(a)

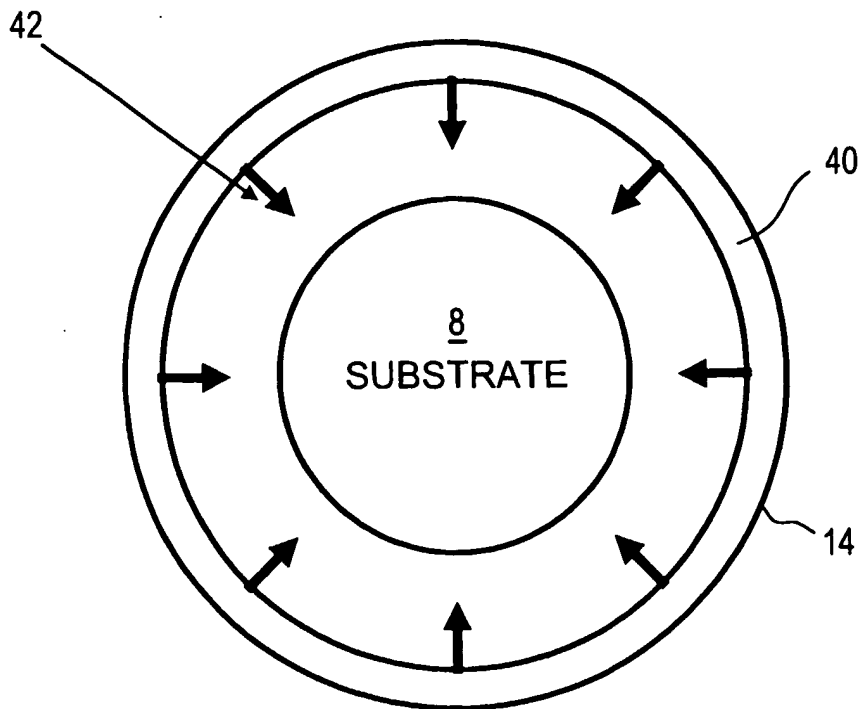
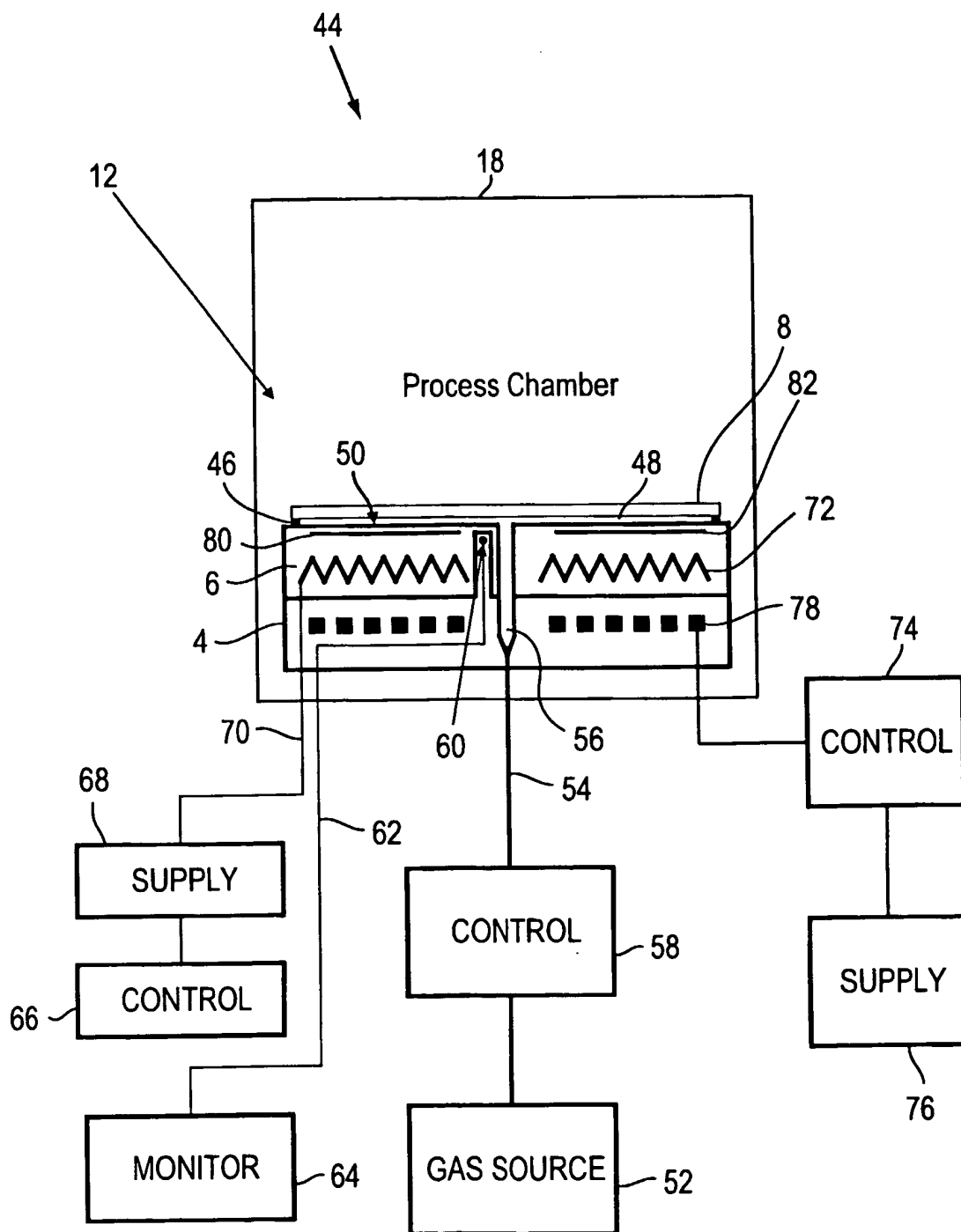


FIG. 5(b)

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**FIG. 6**

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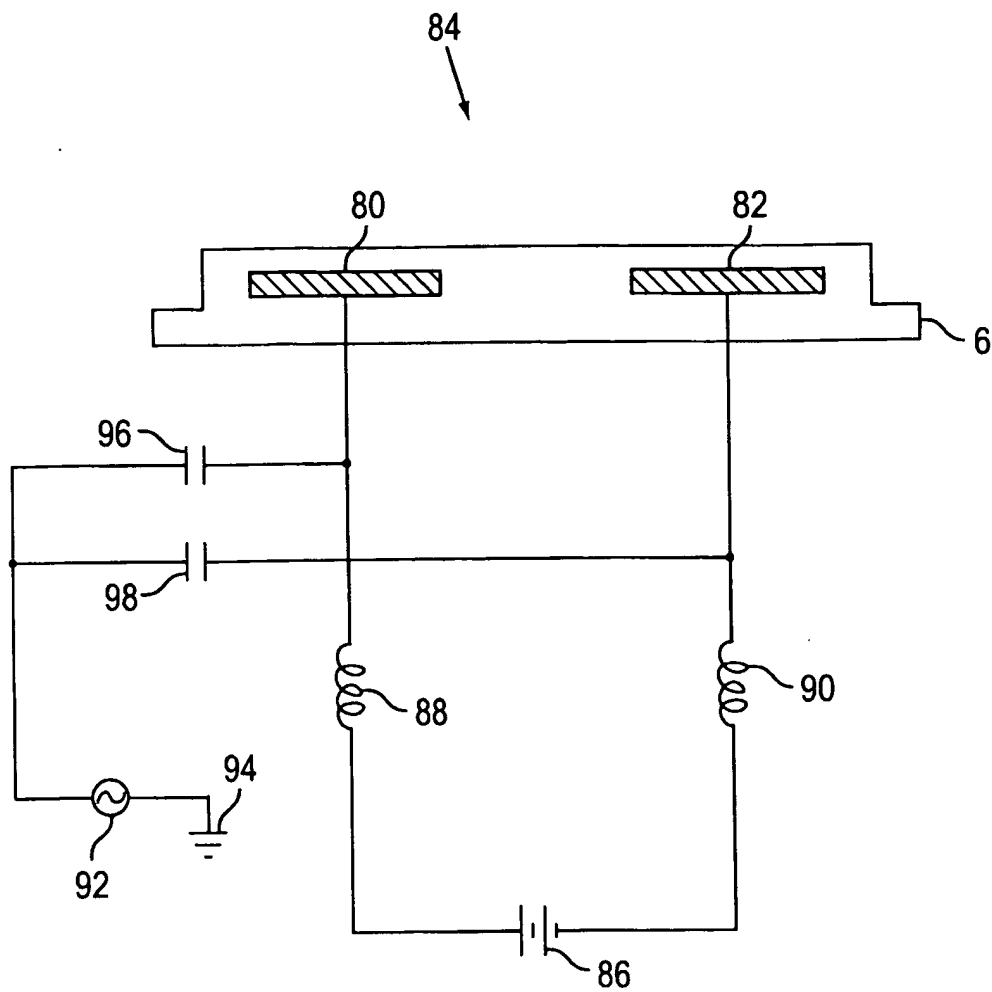


FIG. 7

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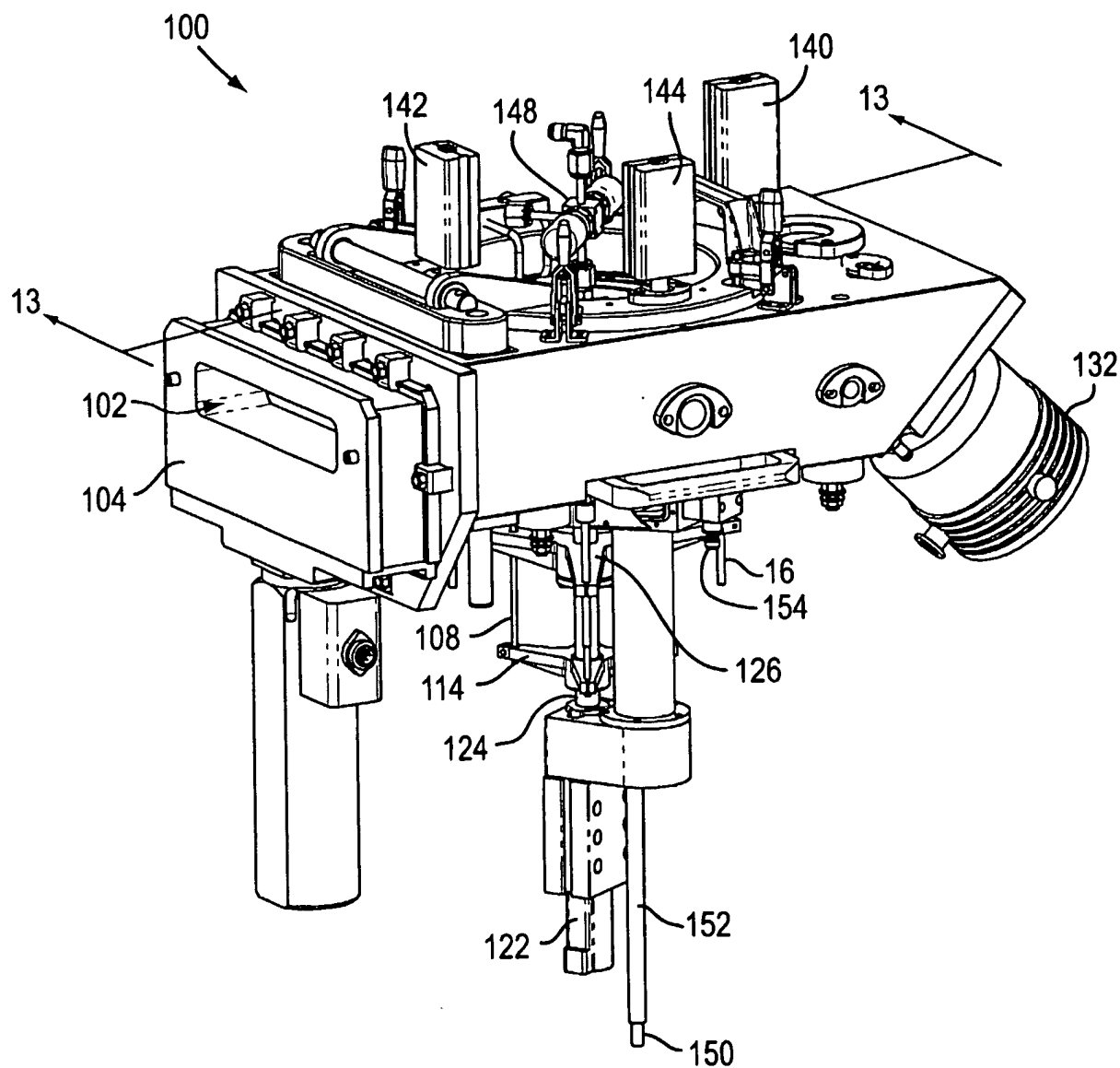


FIG. 8

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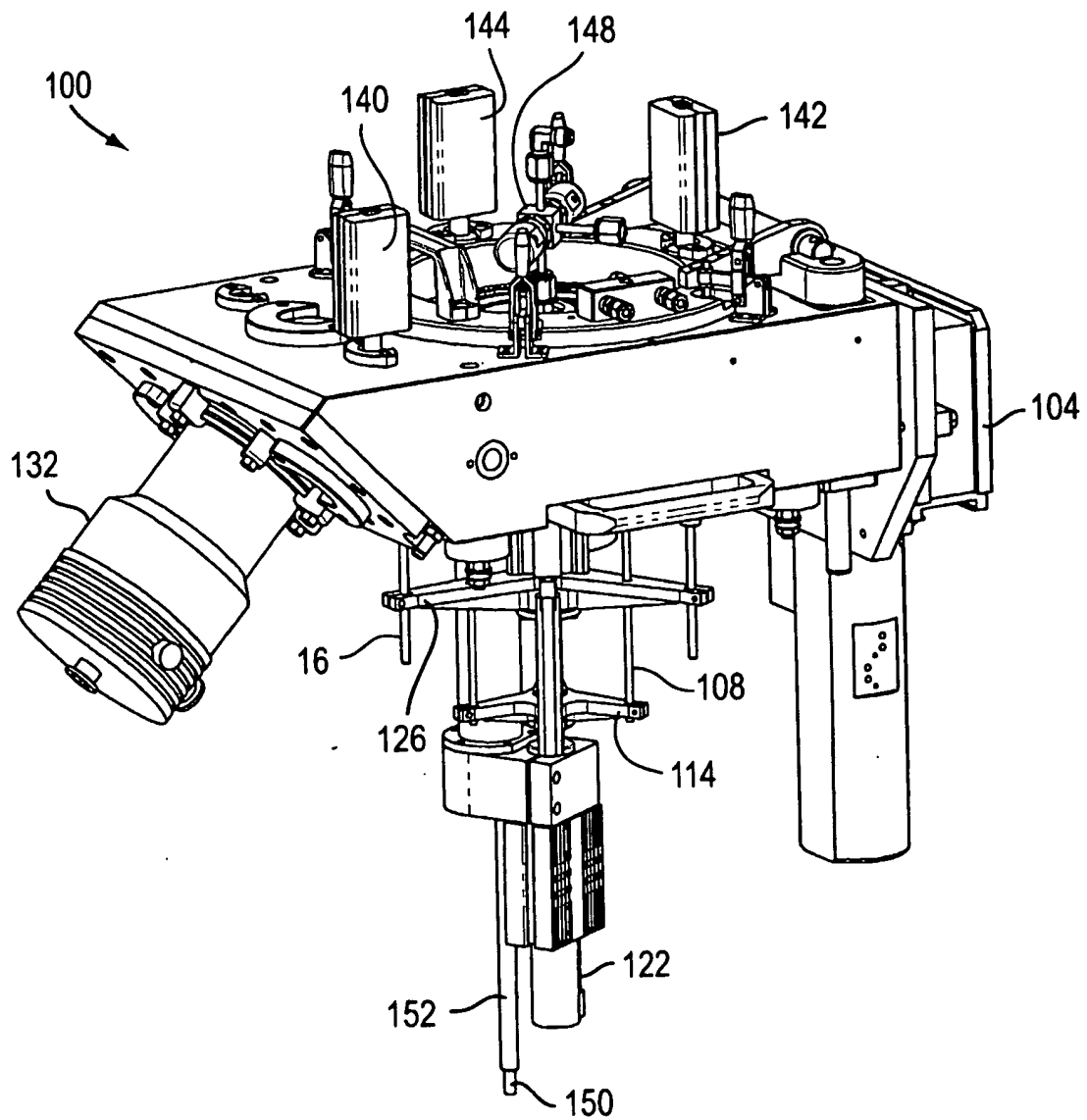


FIG. 9

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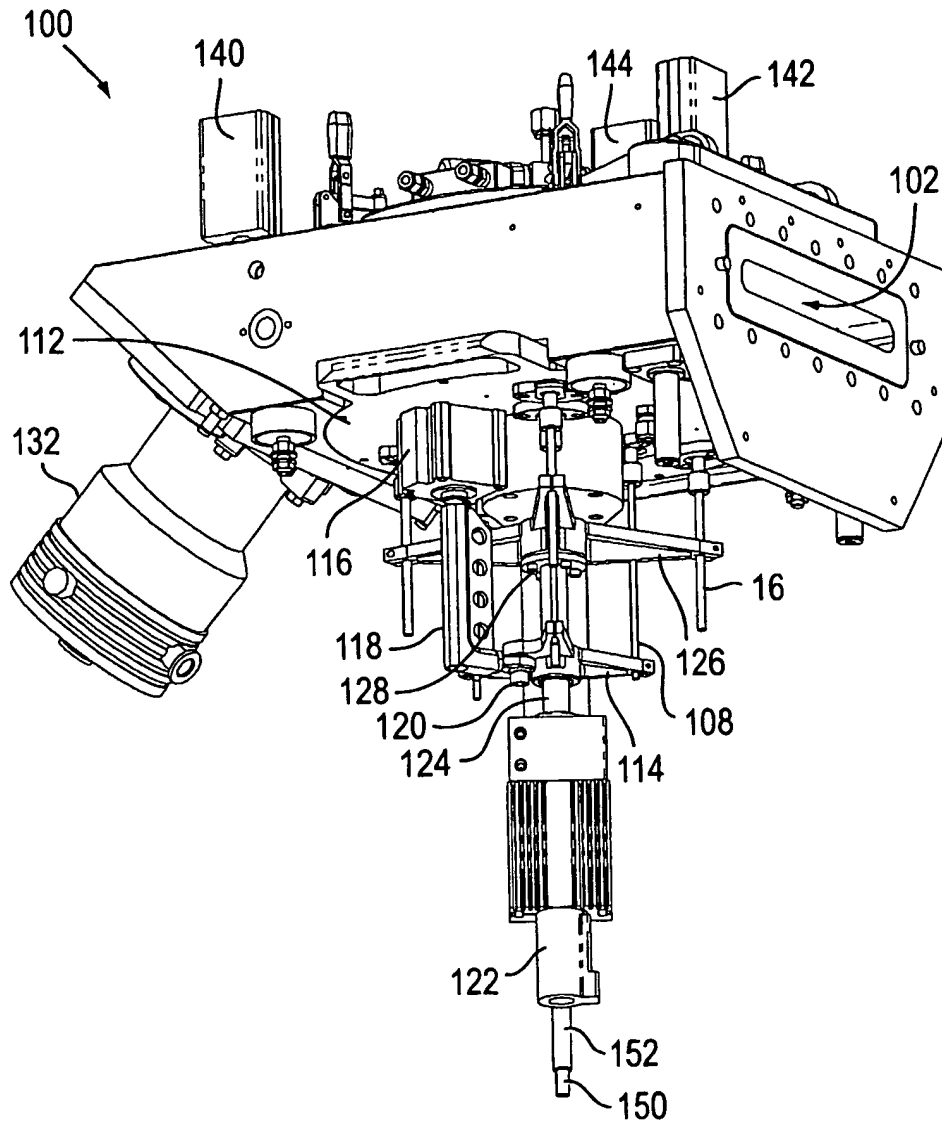


FIG. 10

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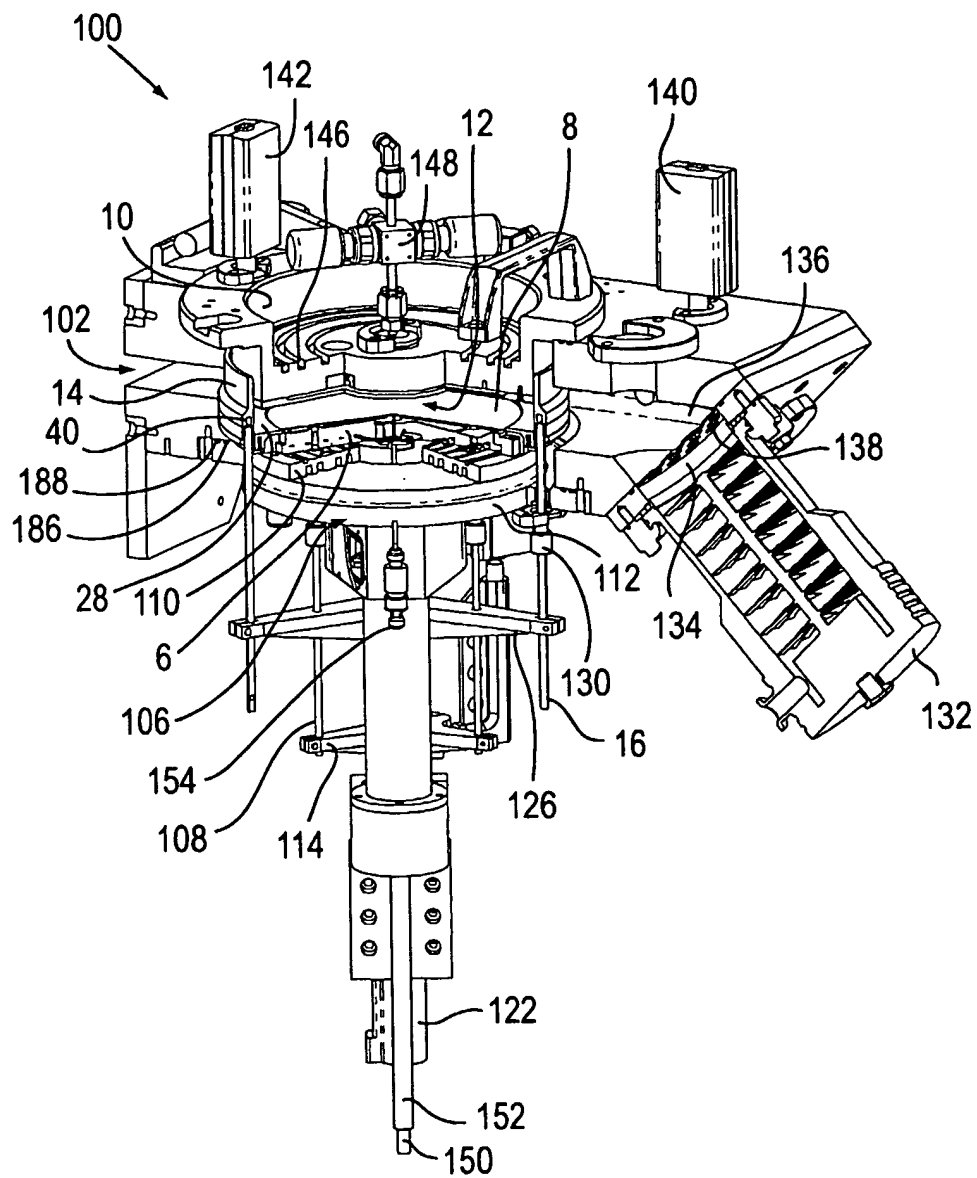


FIG. 12

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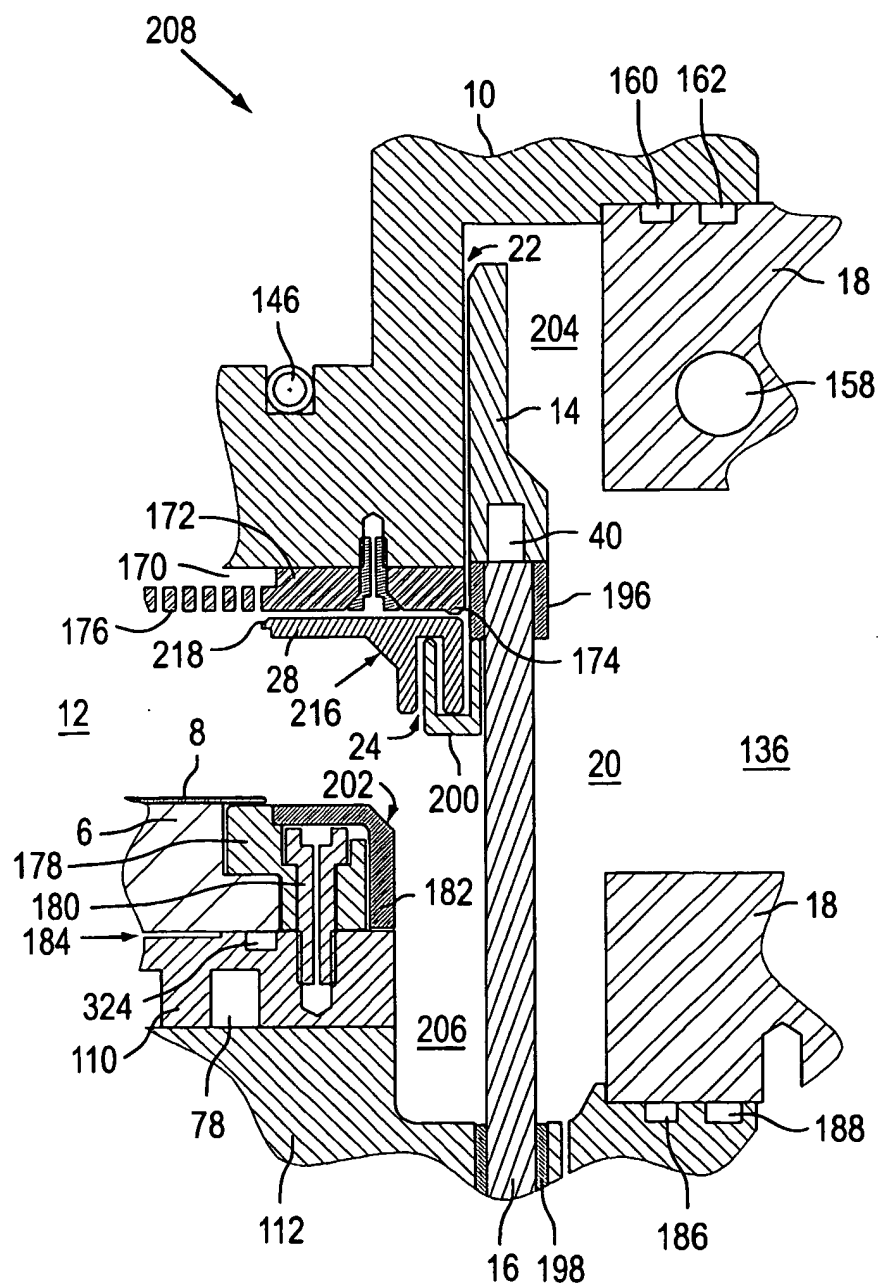


FIG. 14

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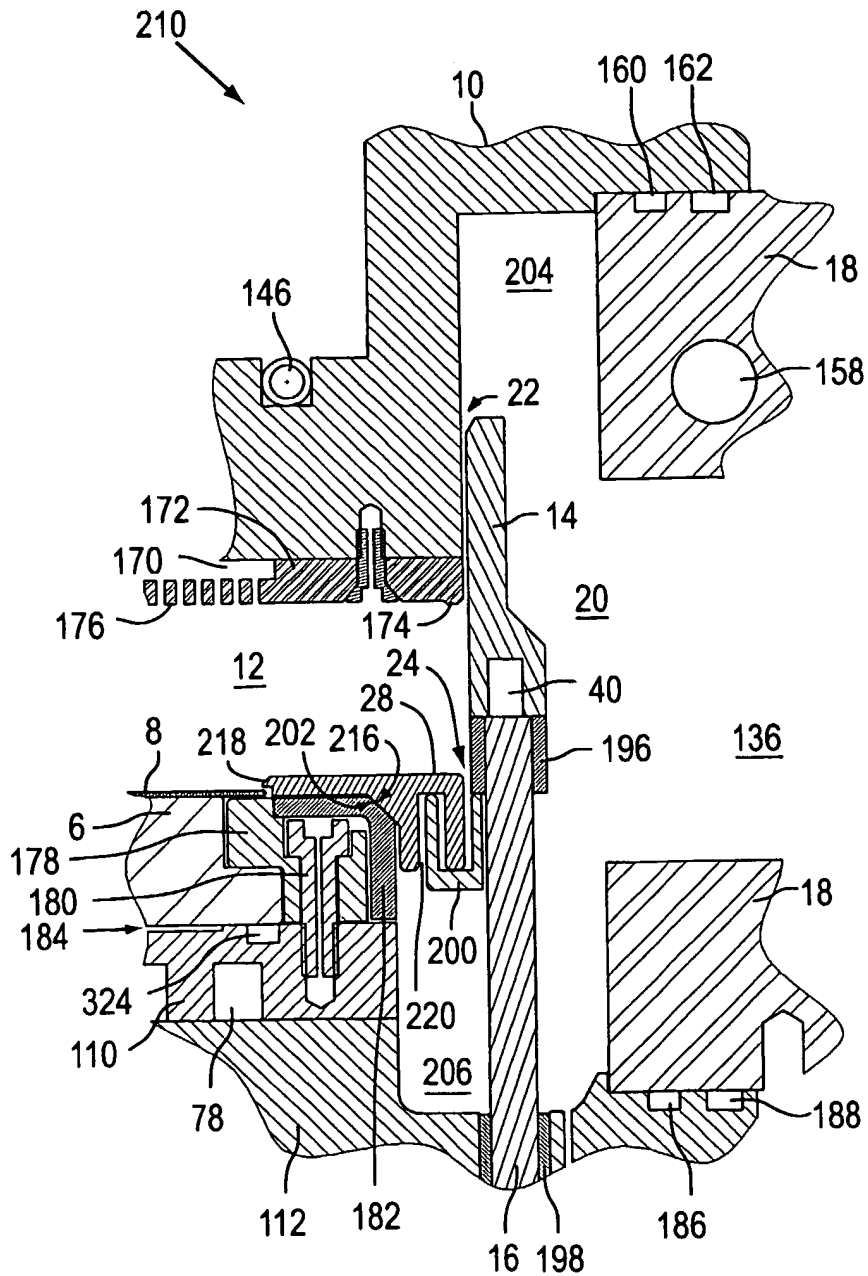


FIG. 15

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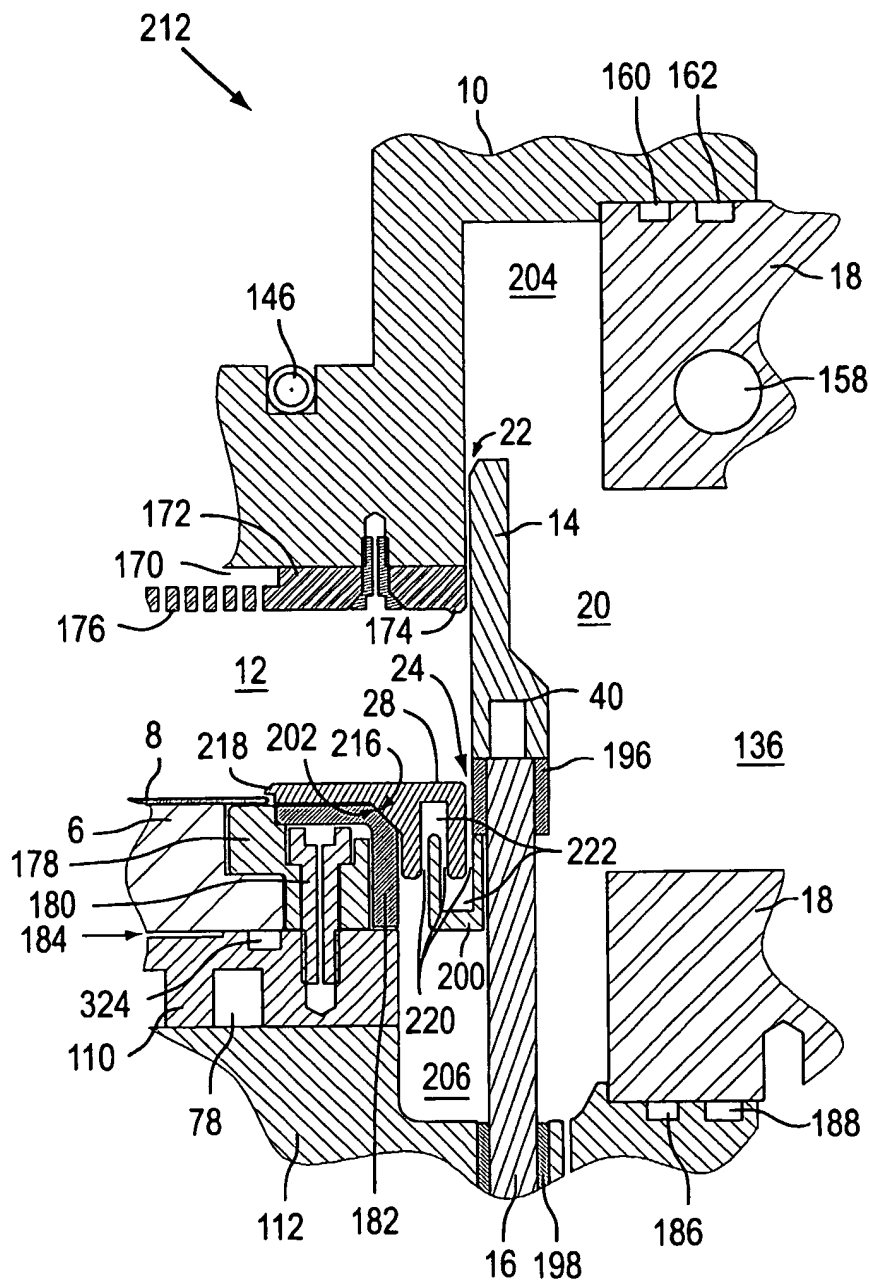


FIG. 16

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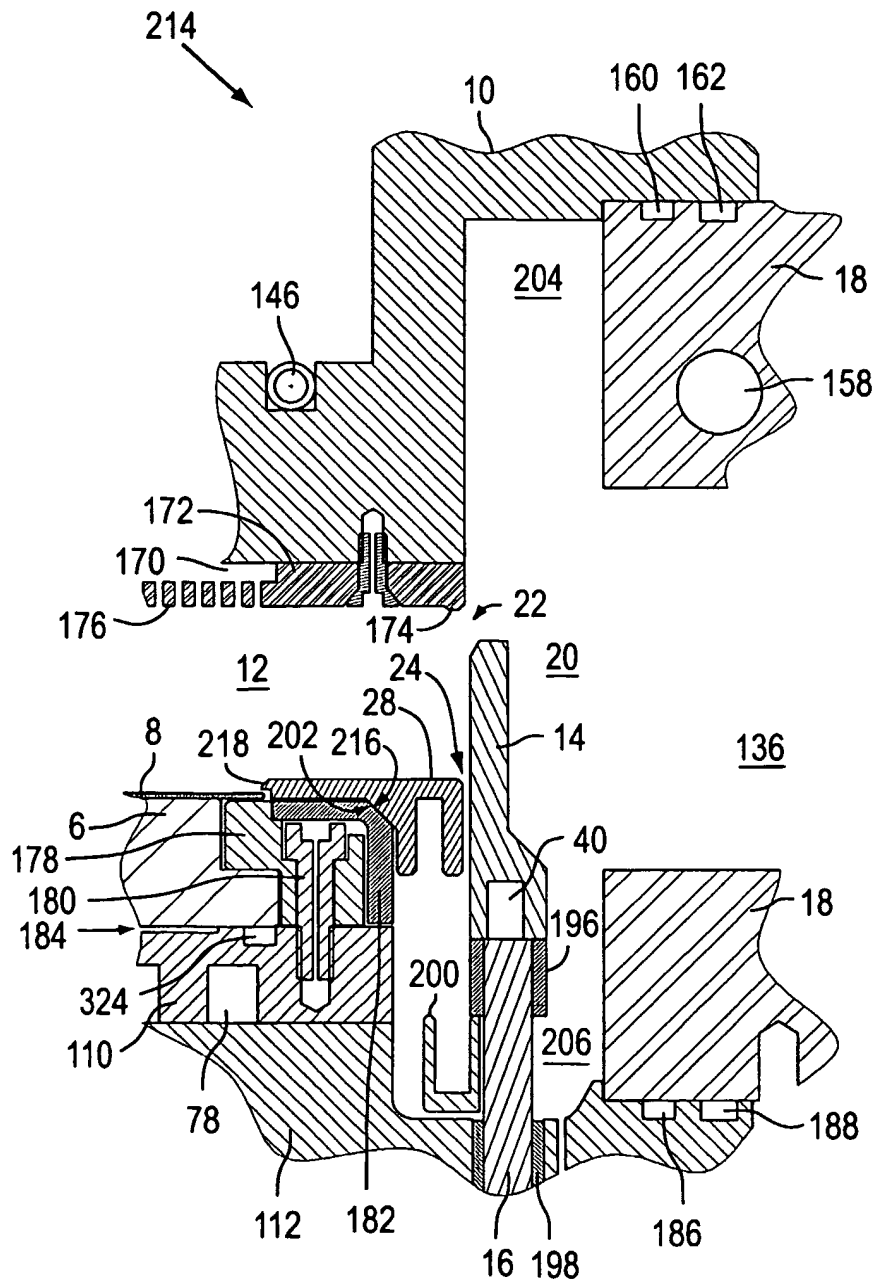


FIG. 17

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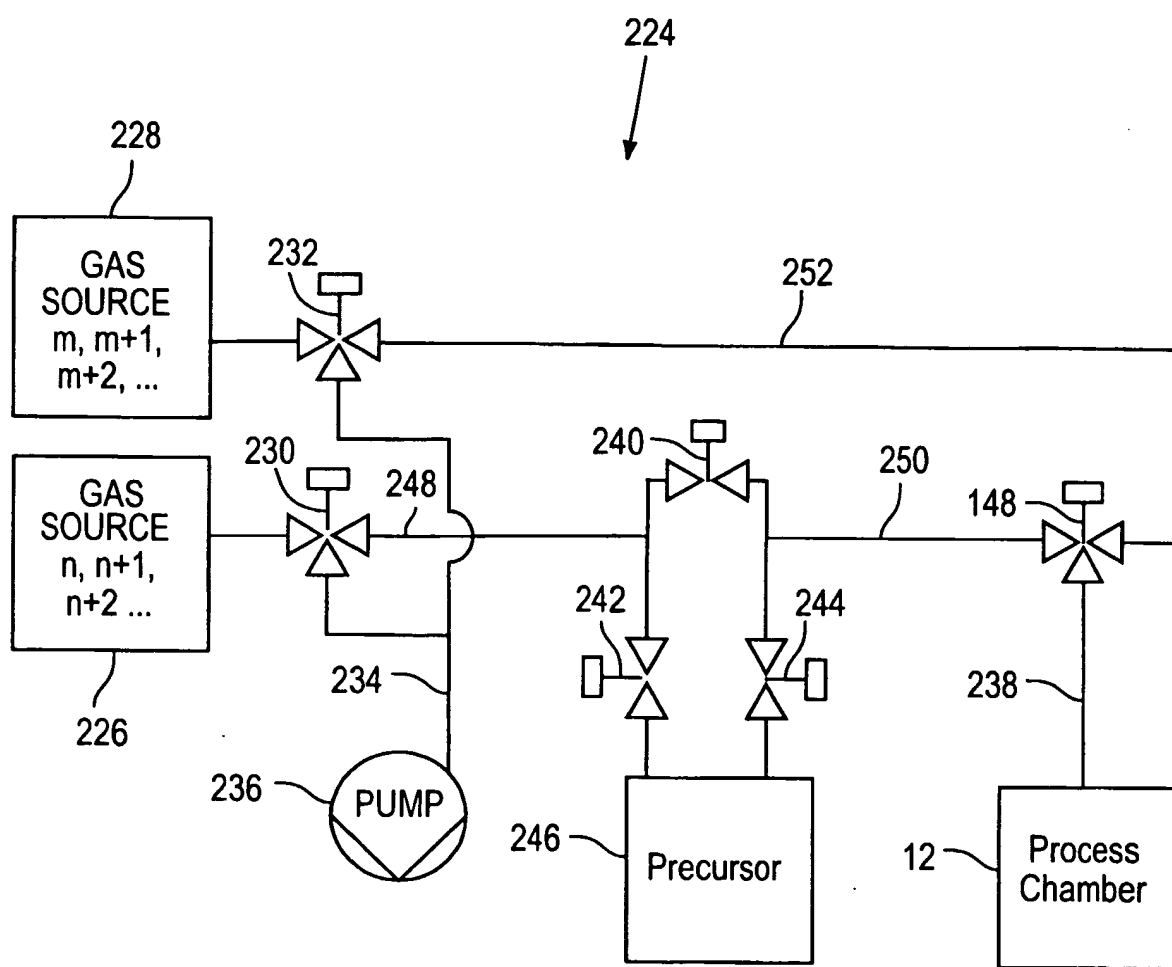


FIG. 18

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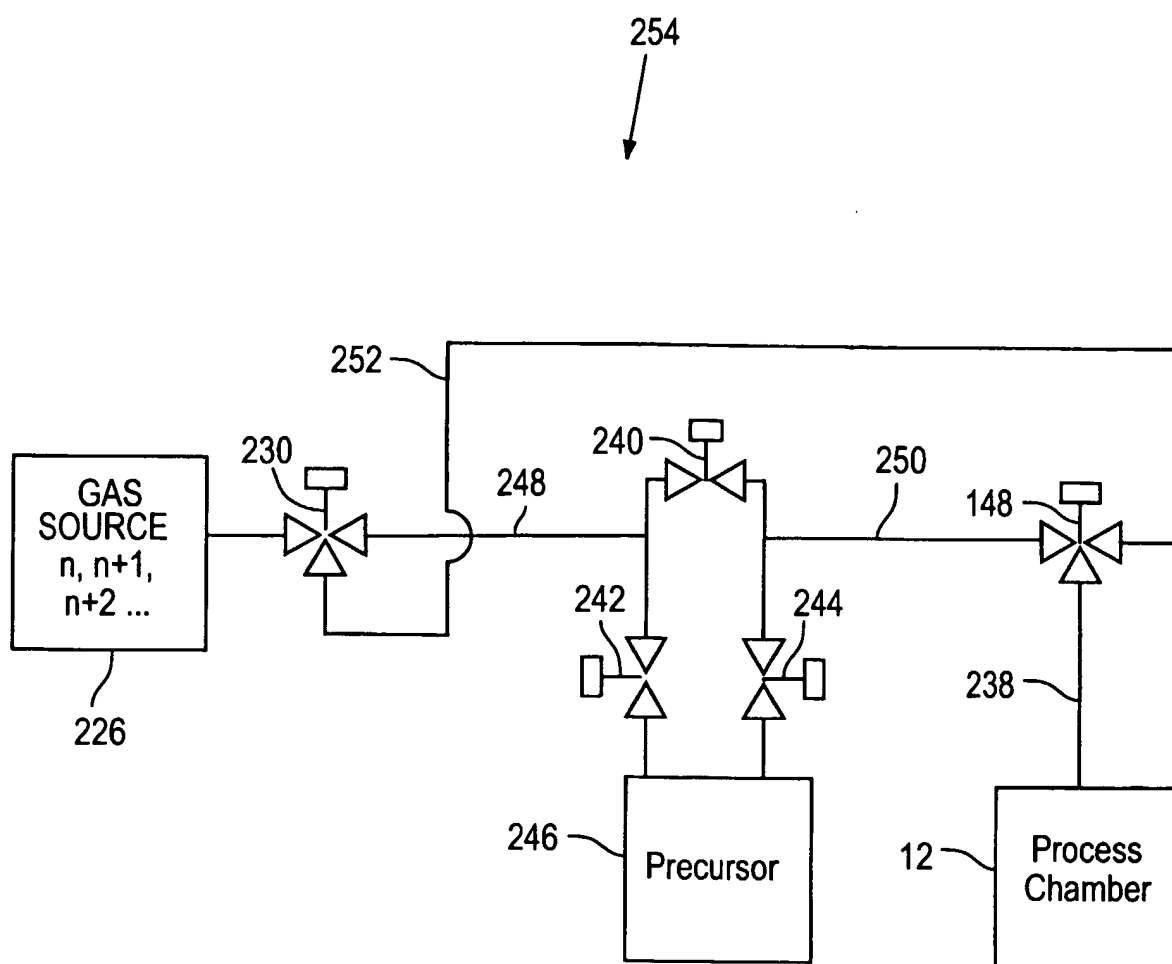


FIG. 19

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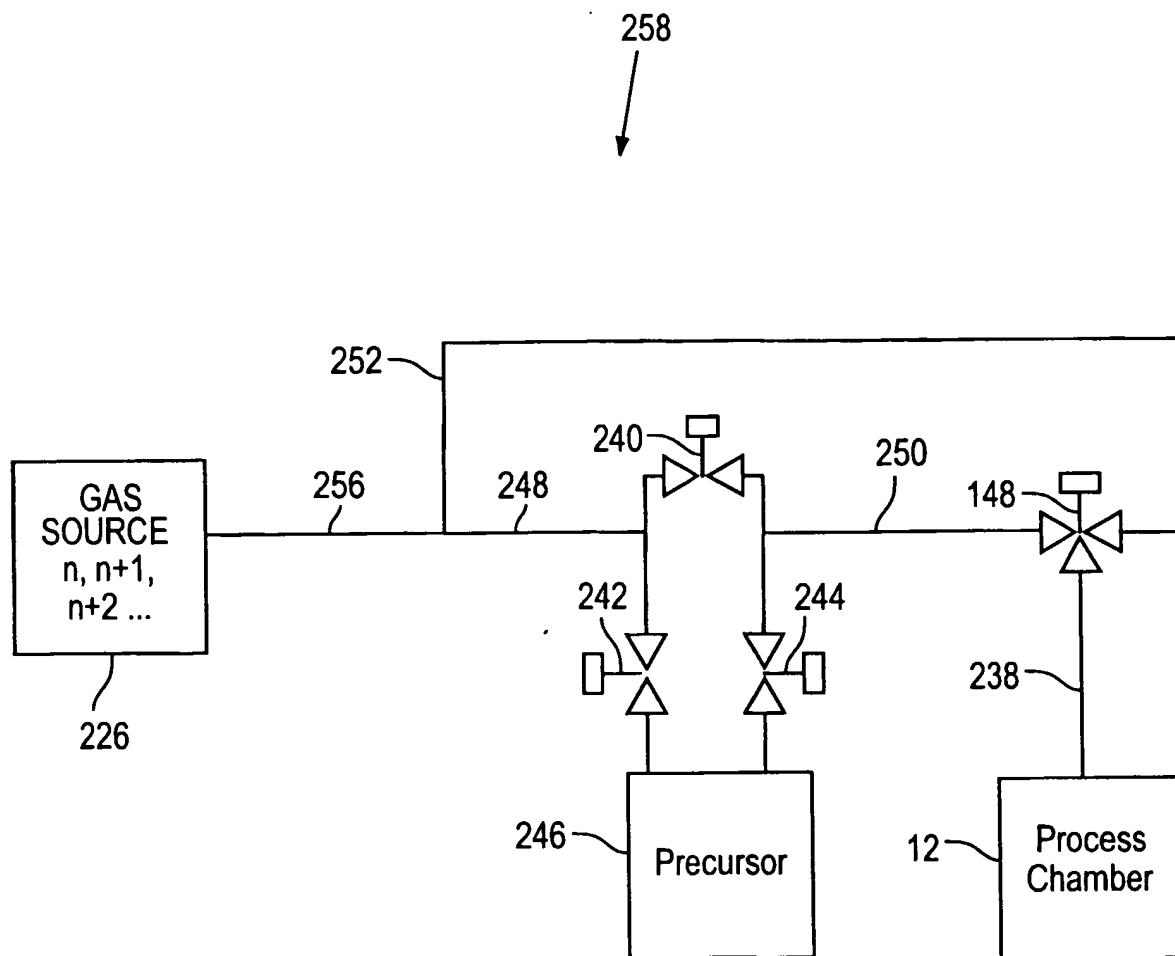
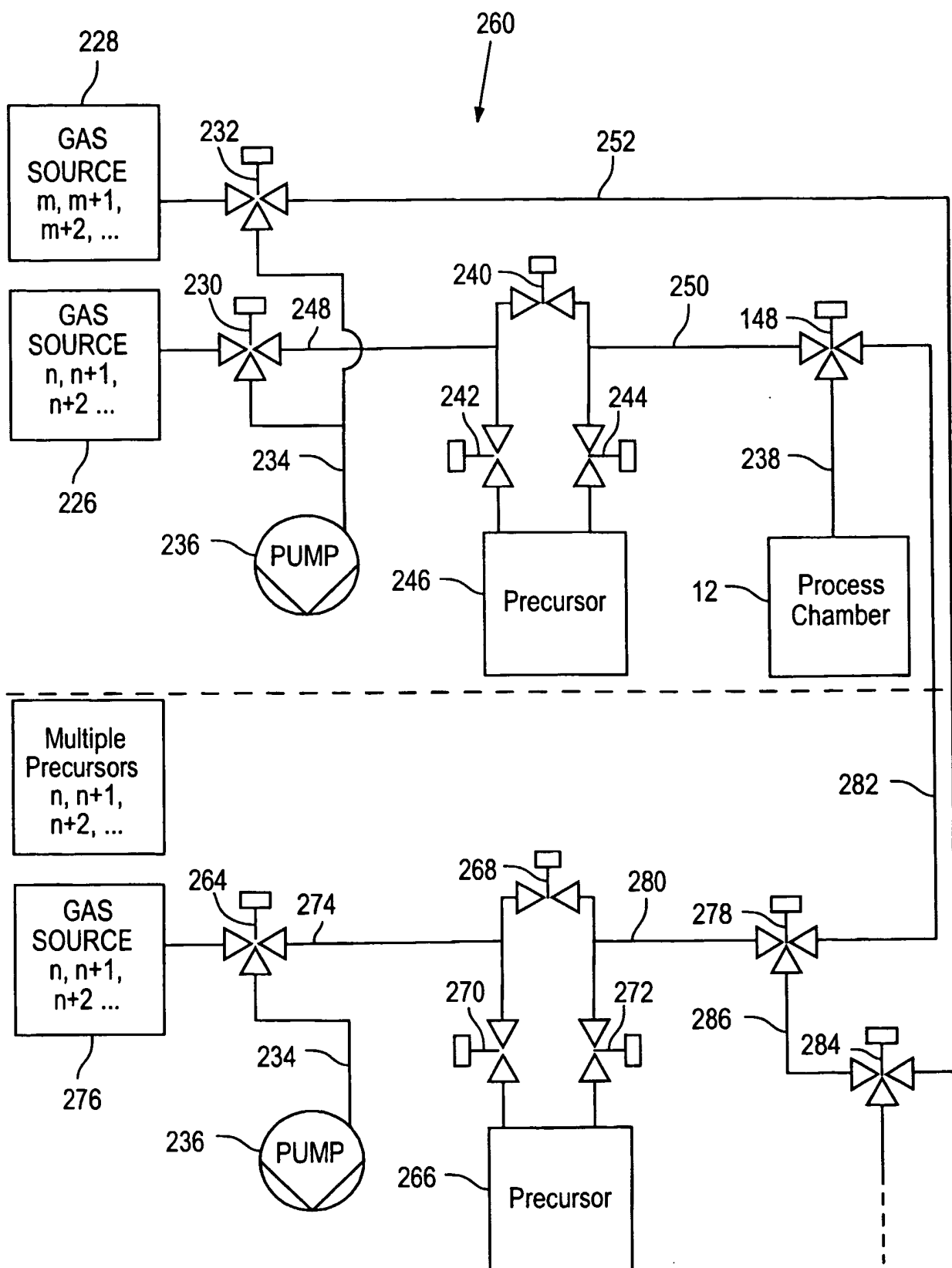
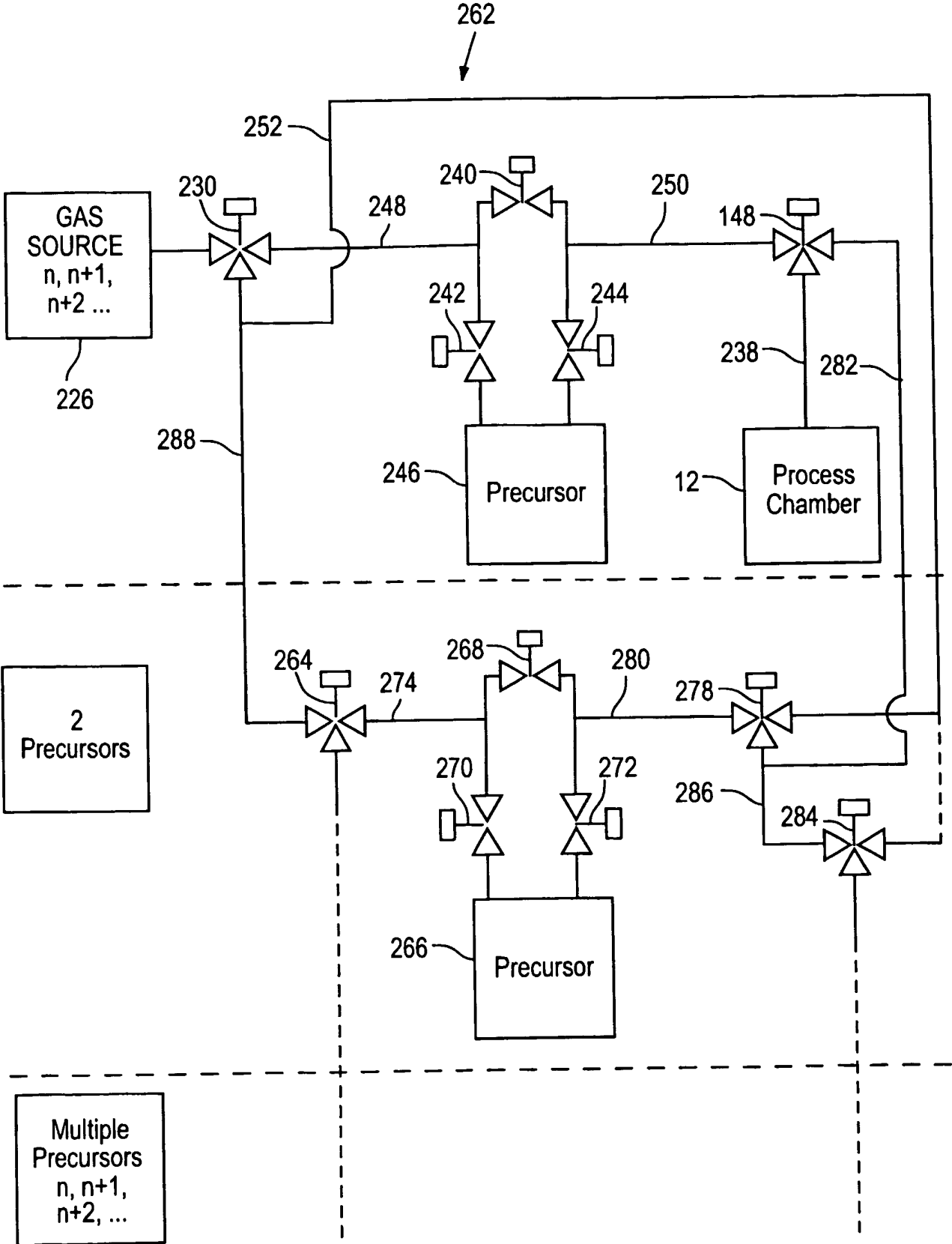


FIG. 20

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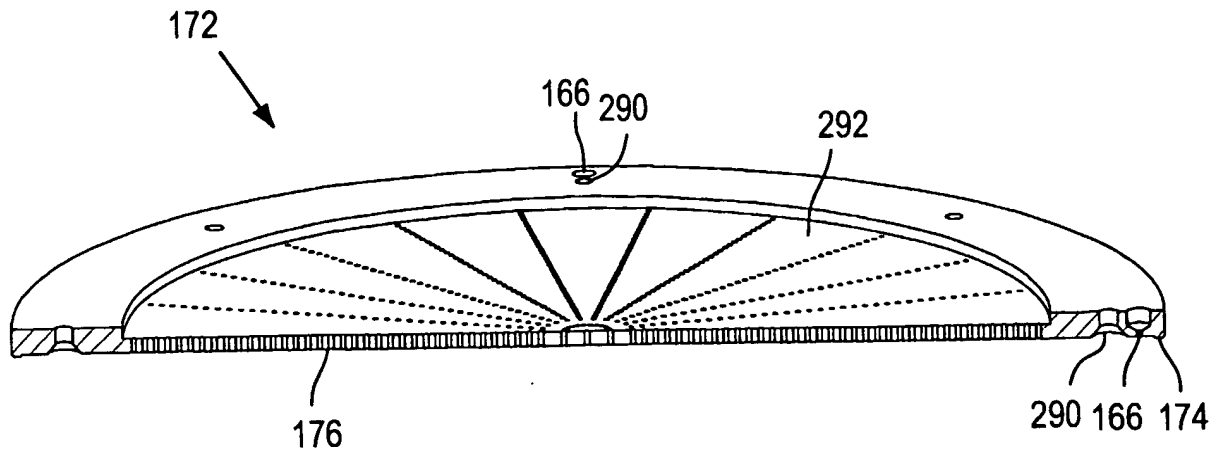


FIG. 23(a)

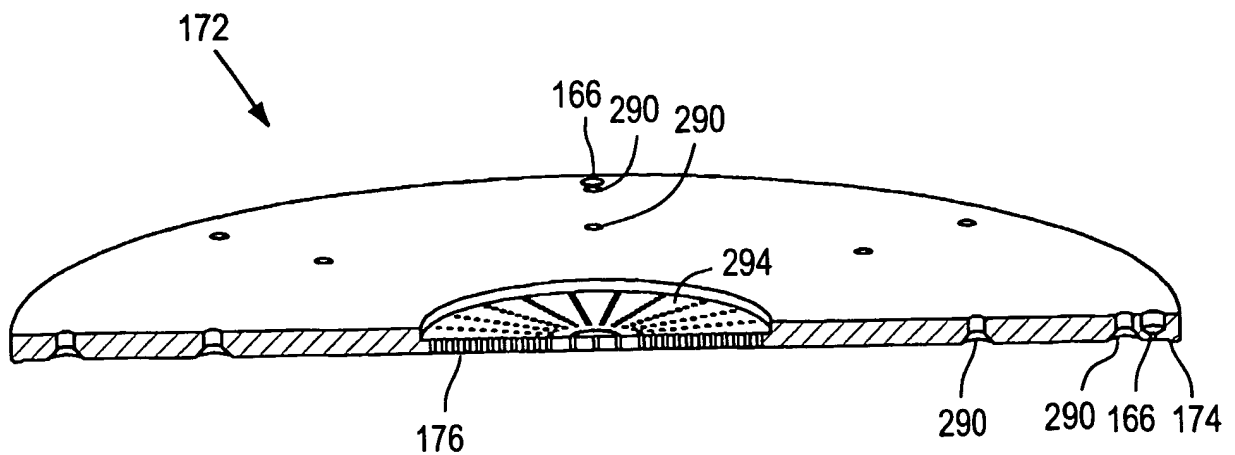


FIG. 23(b)

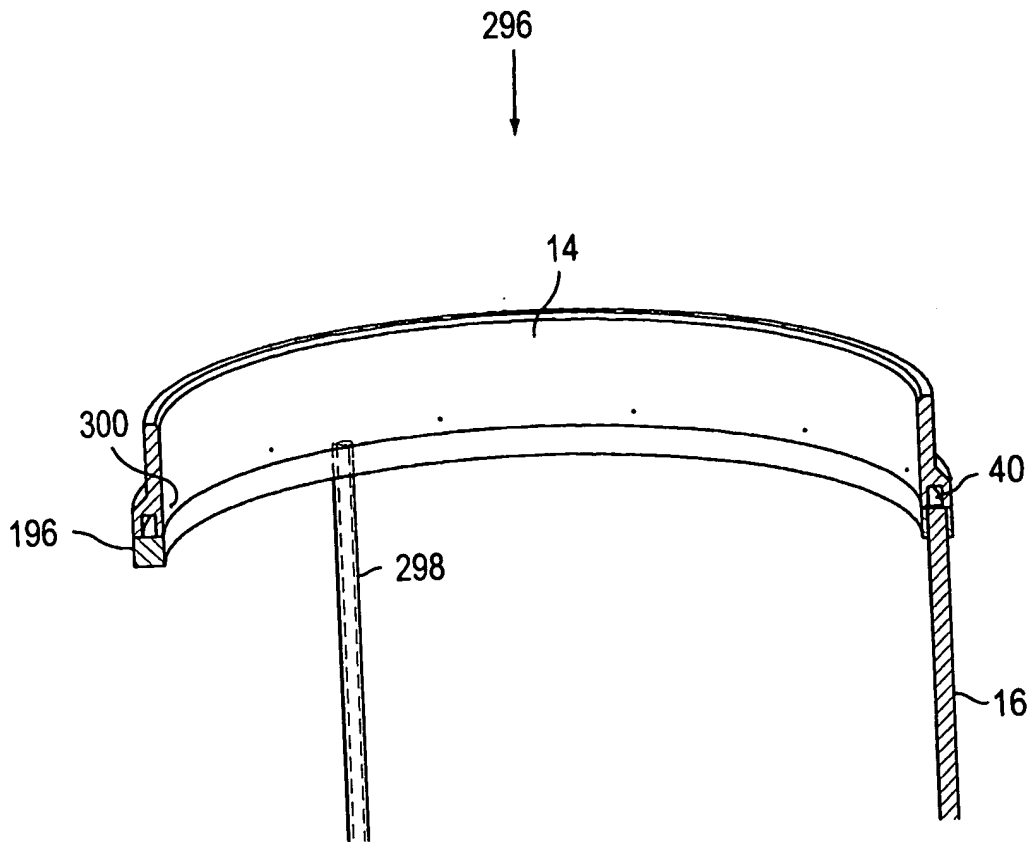


FIG. 24

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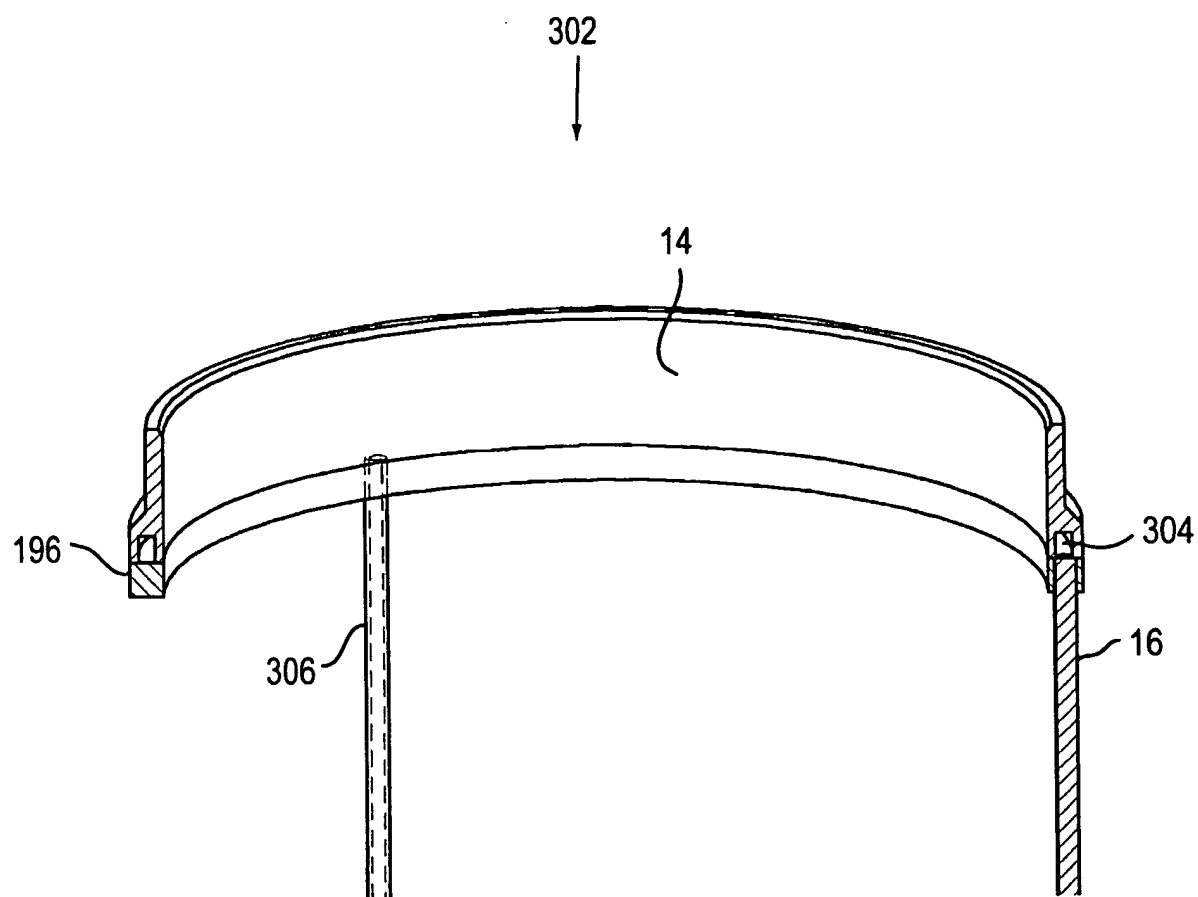


FIG. 25

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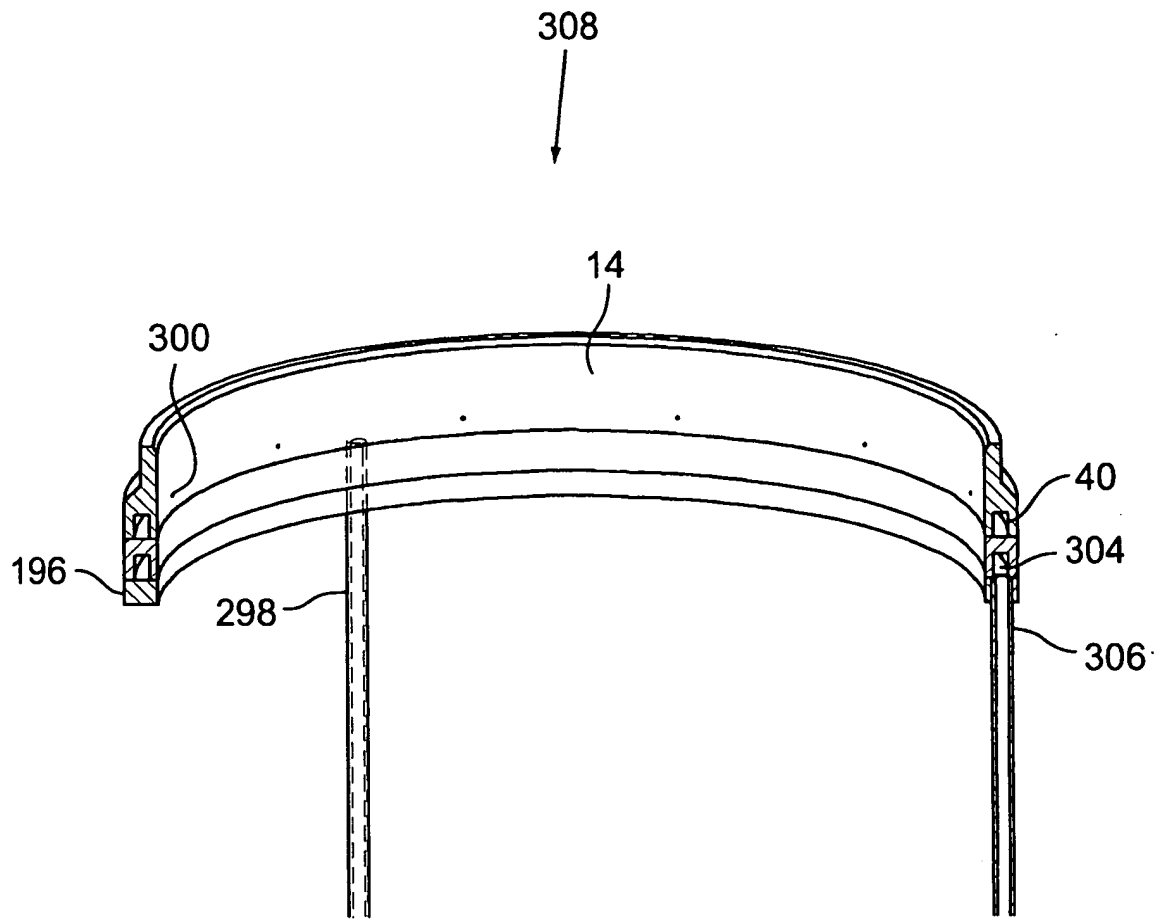
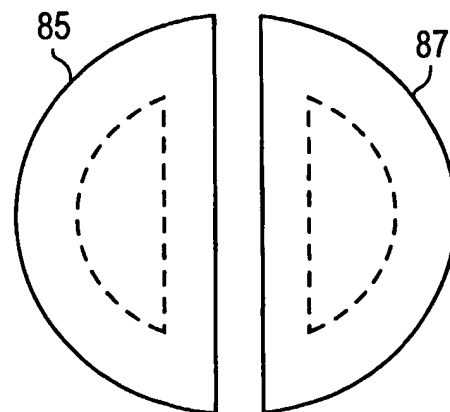
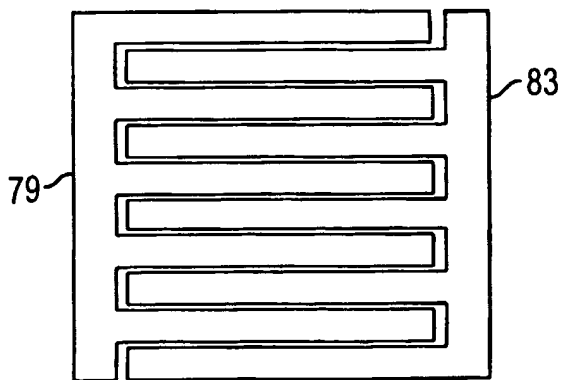
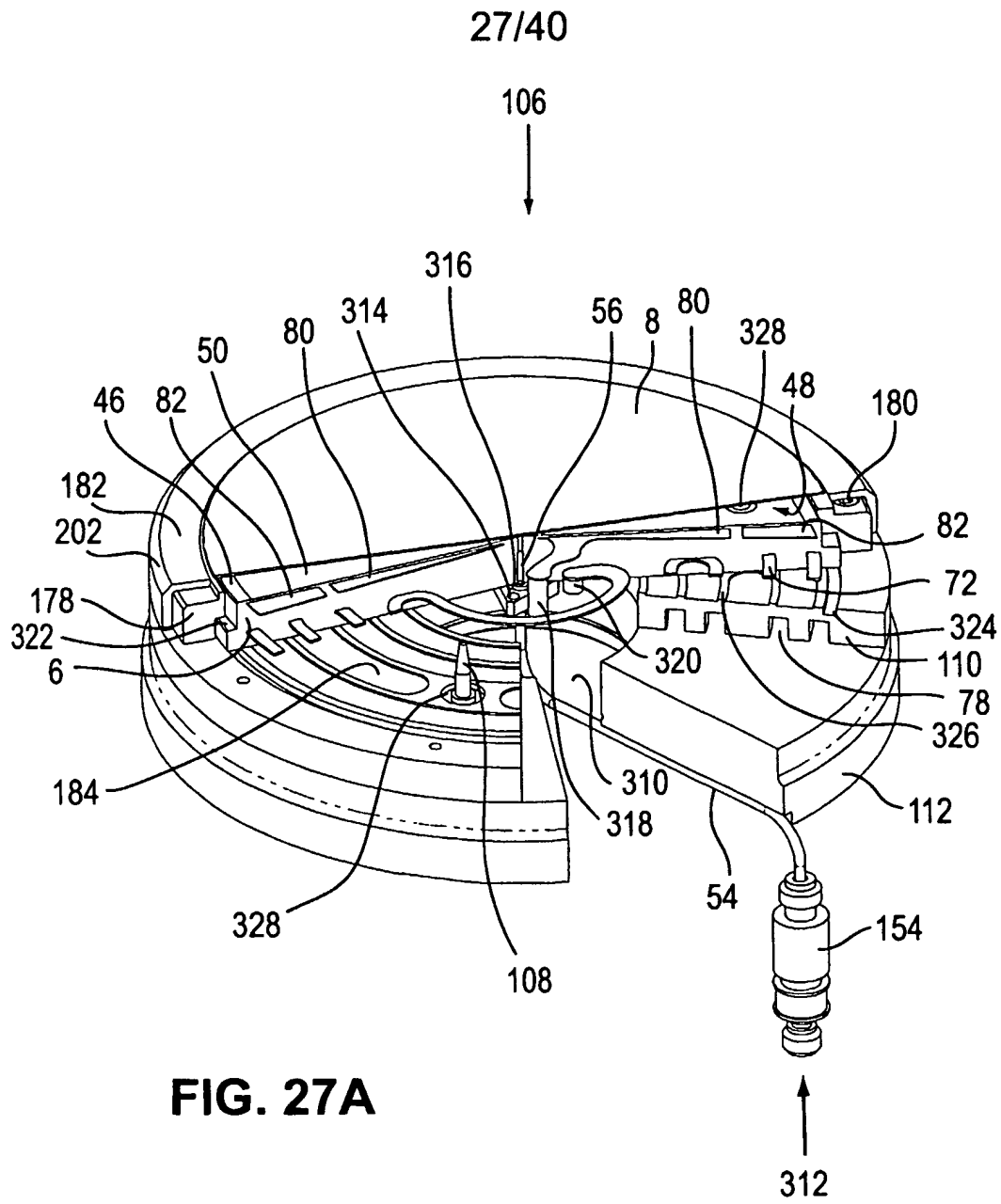


FIG. 26



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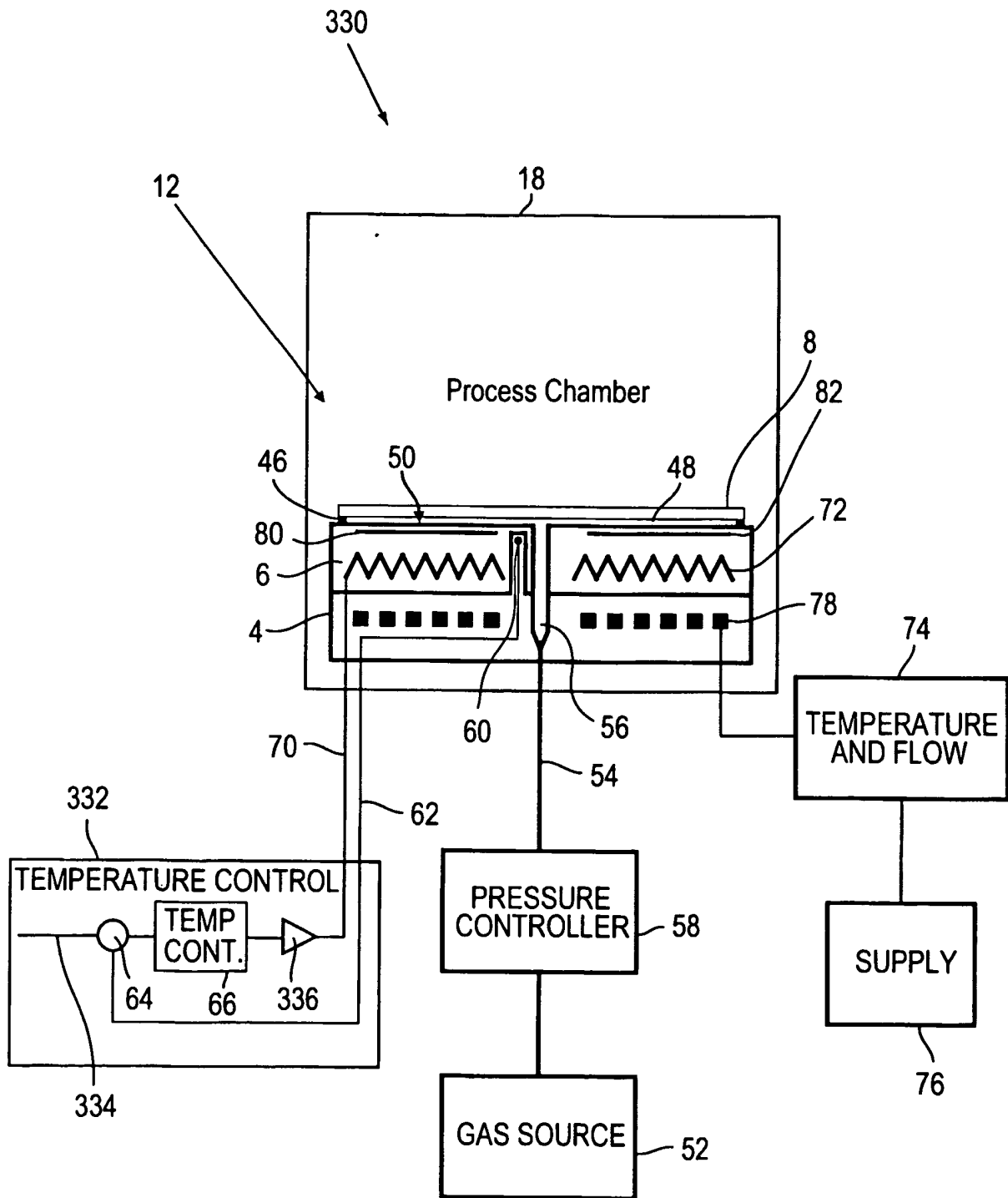


FIG. 28

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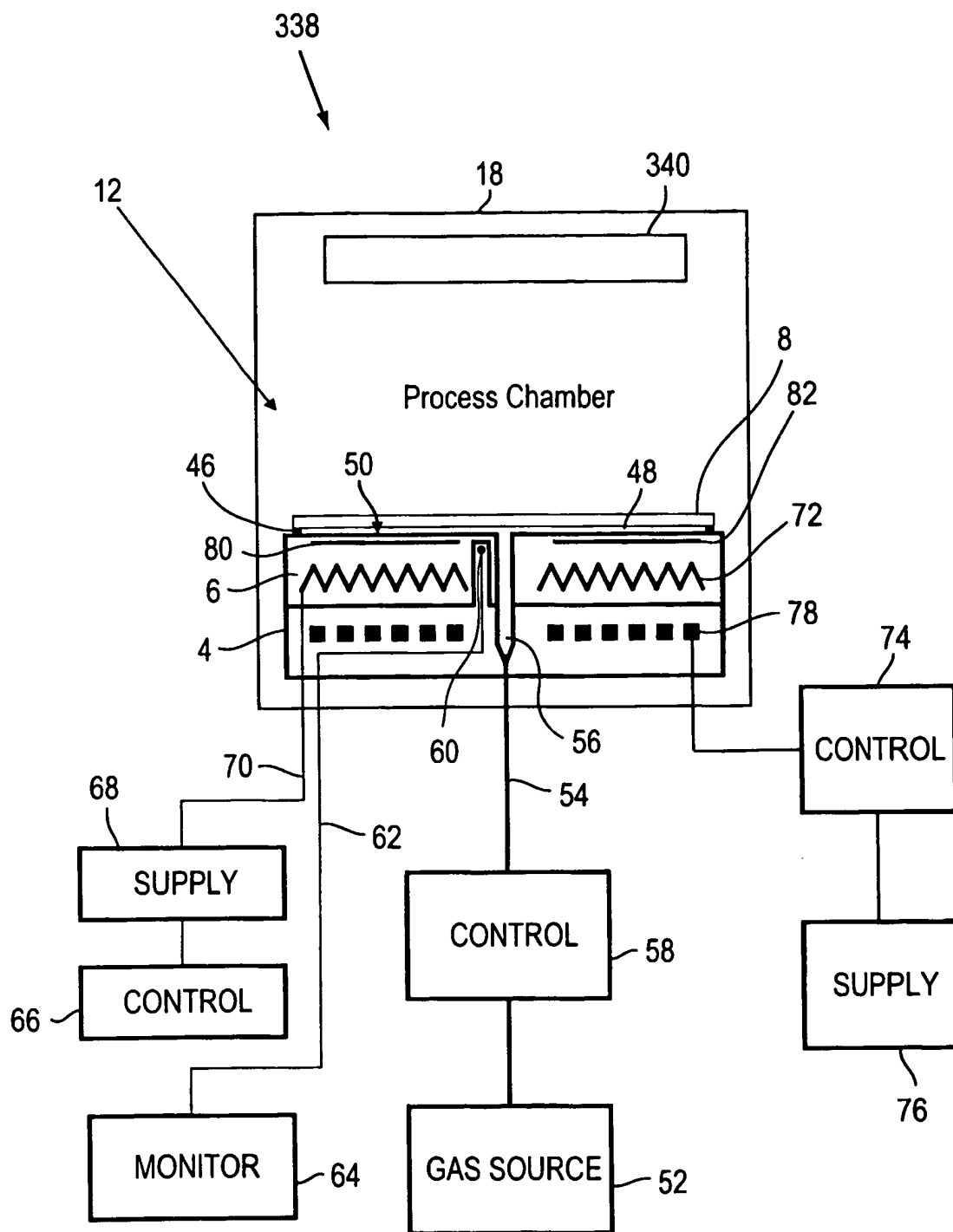


FIG. 29

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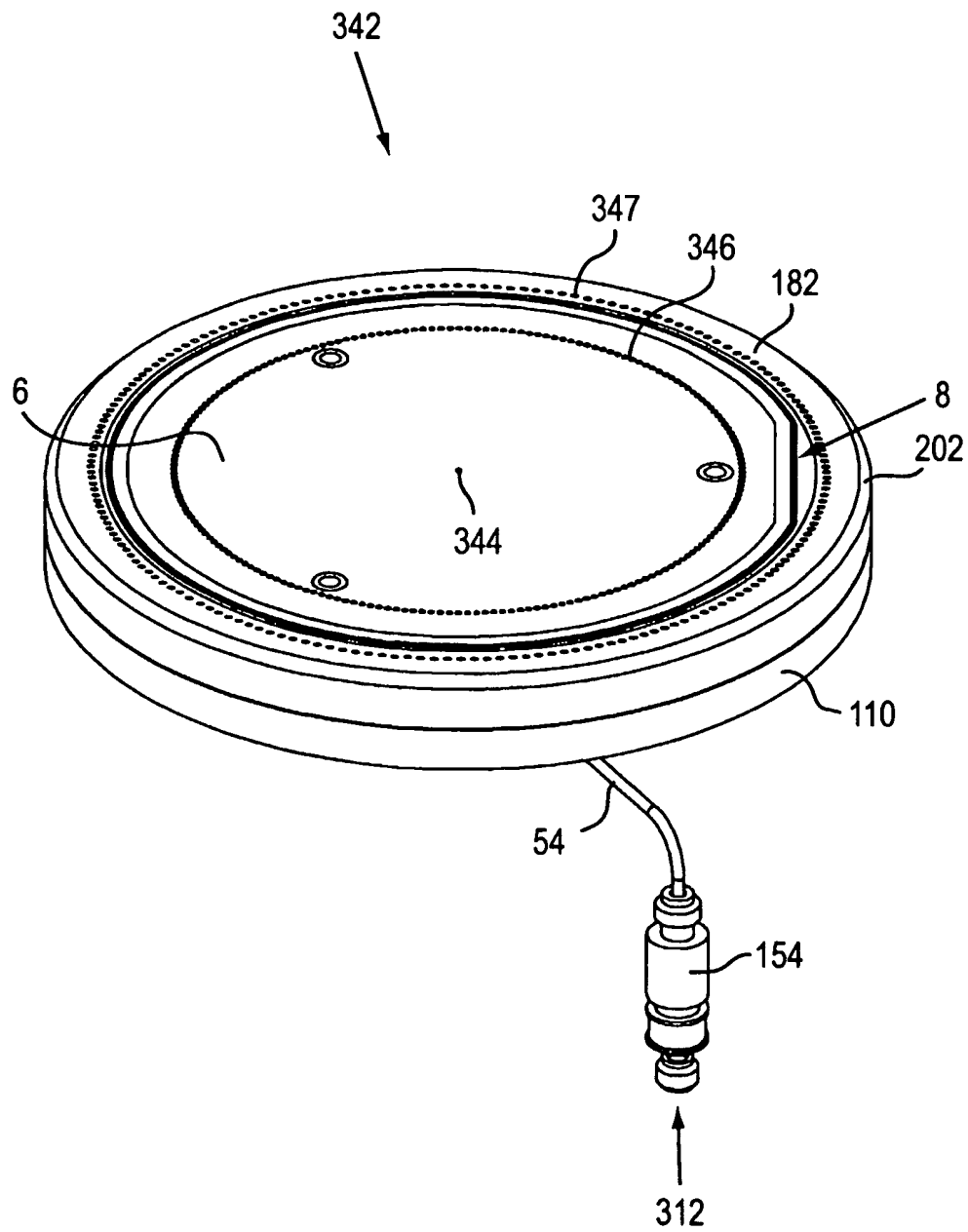


FIG. 30

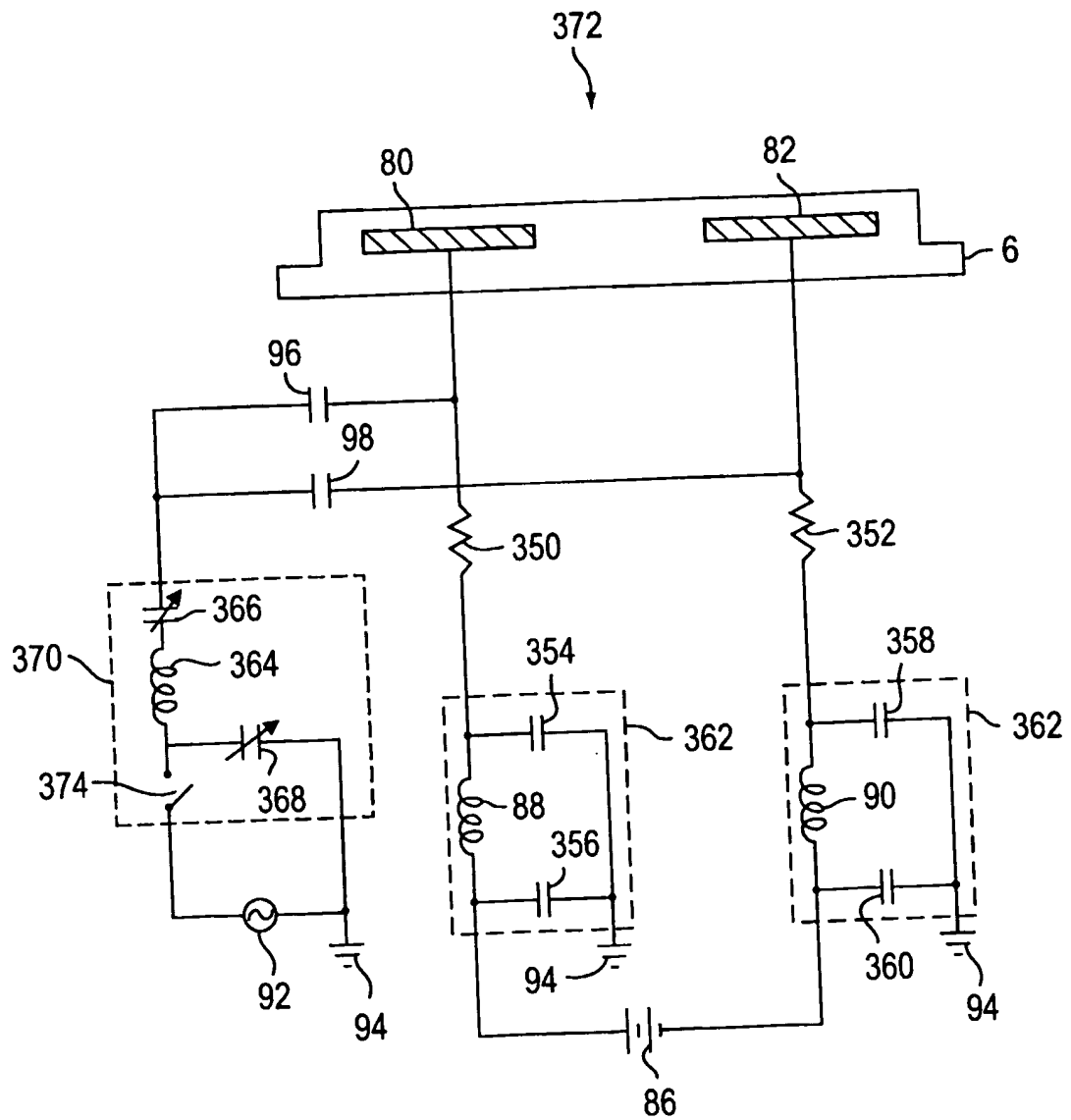


FIG. 32

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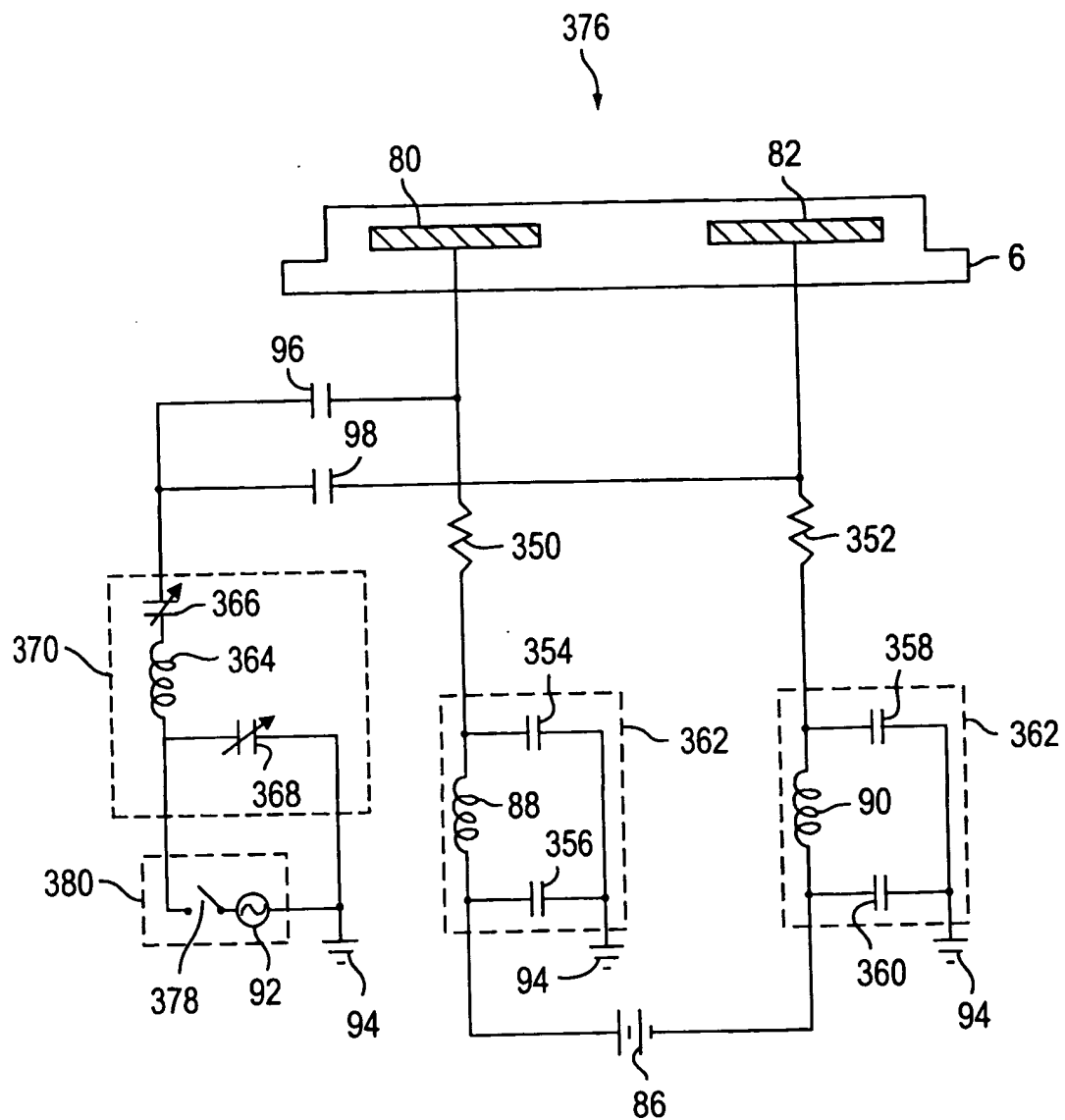


FIG. 33

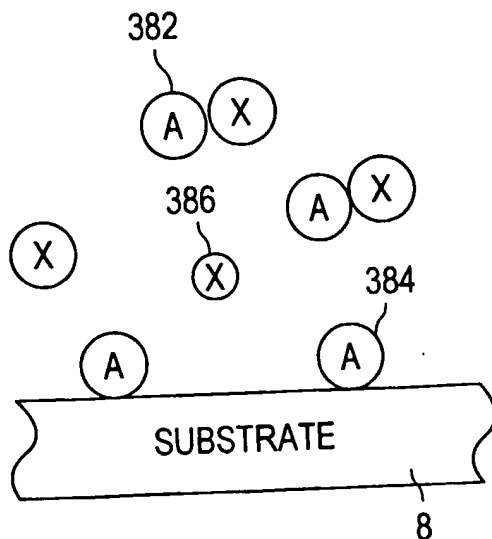


FIG. 34(a)
(PRIOR ART)

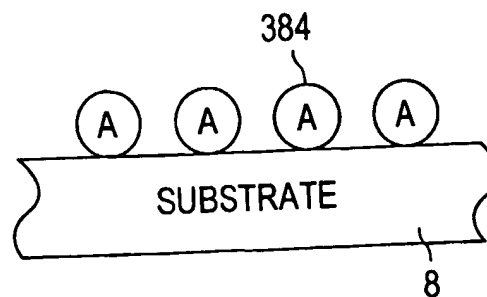


FIG. 34(b)
(PRIOR ART)

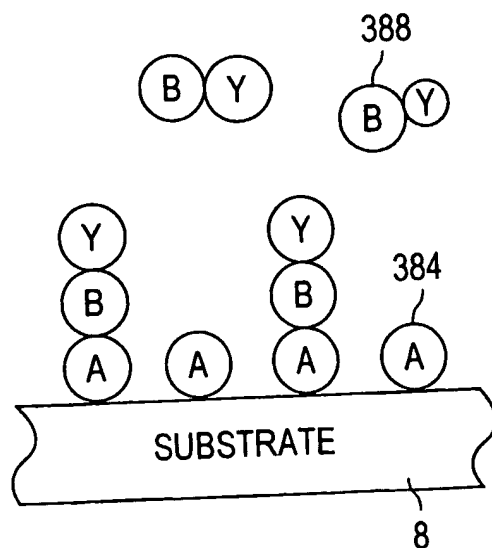


FIG. 34(c)
(PRIOR ART)

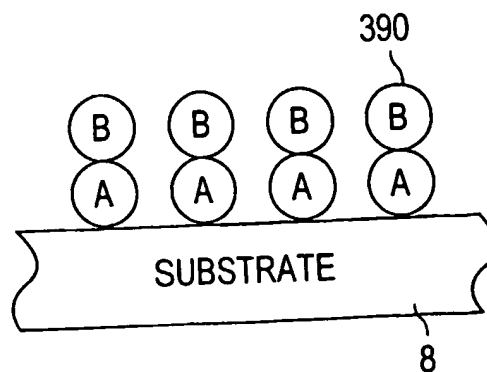


FIG. 34(d)
(PRIOR ART)

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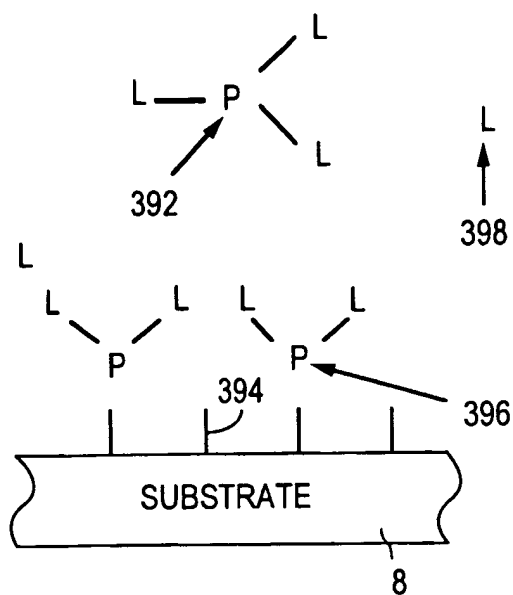


FIG. 35(a)

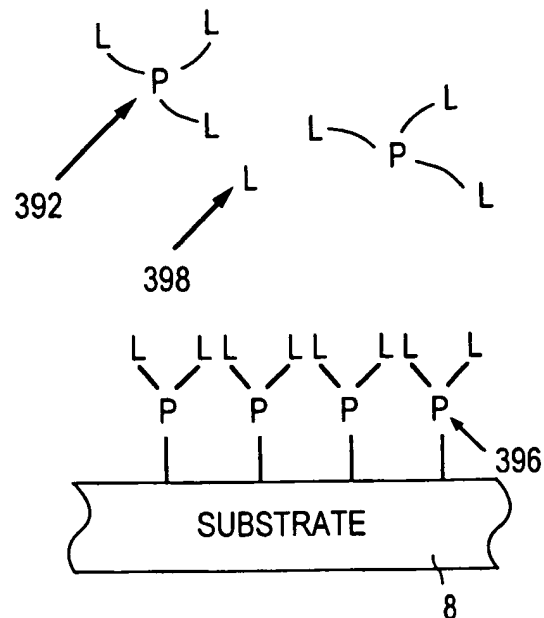


FIG. 35(b)

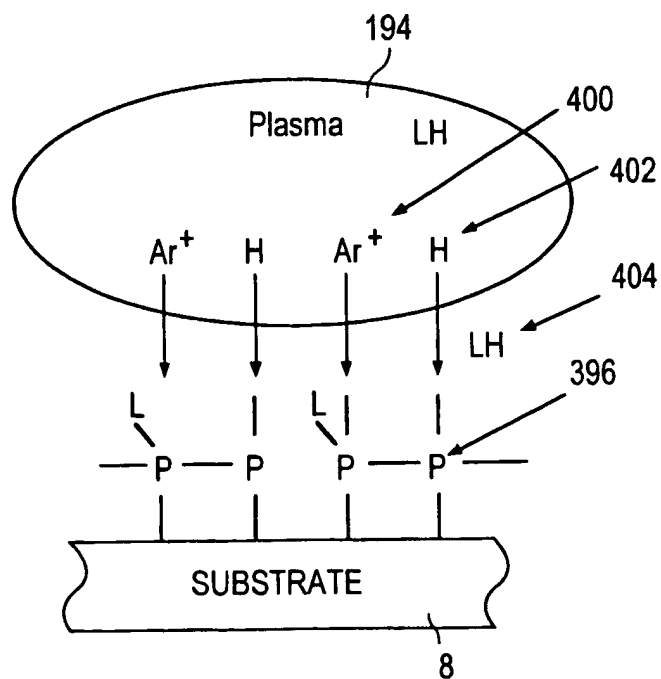


FIG. 35(c)

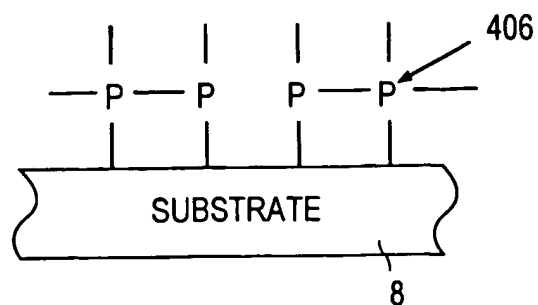


FIG. 35(d)

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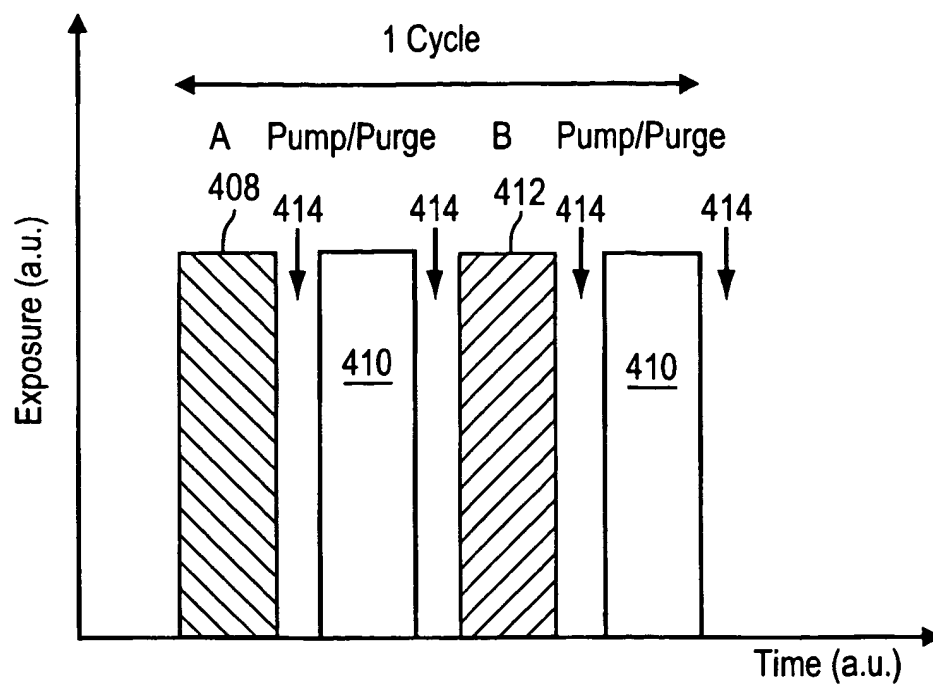


FIG. 36(a)
(PRIOR ART)

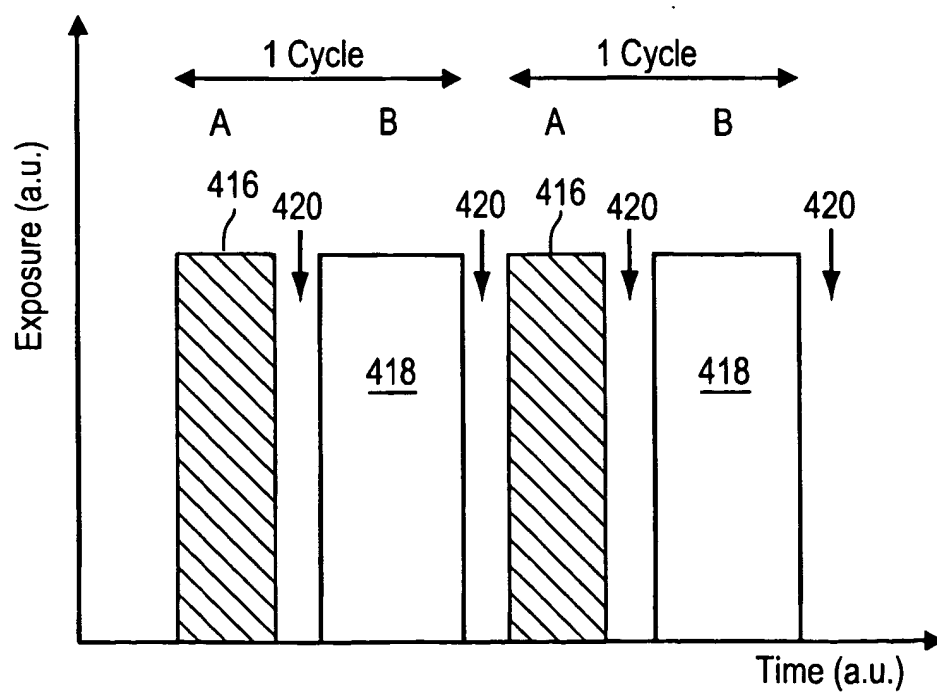


FIG. 36(b)
(PRIOR ART)

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FIG. 37(a)

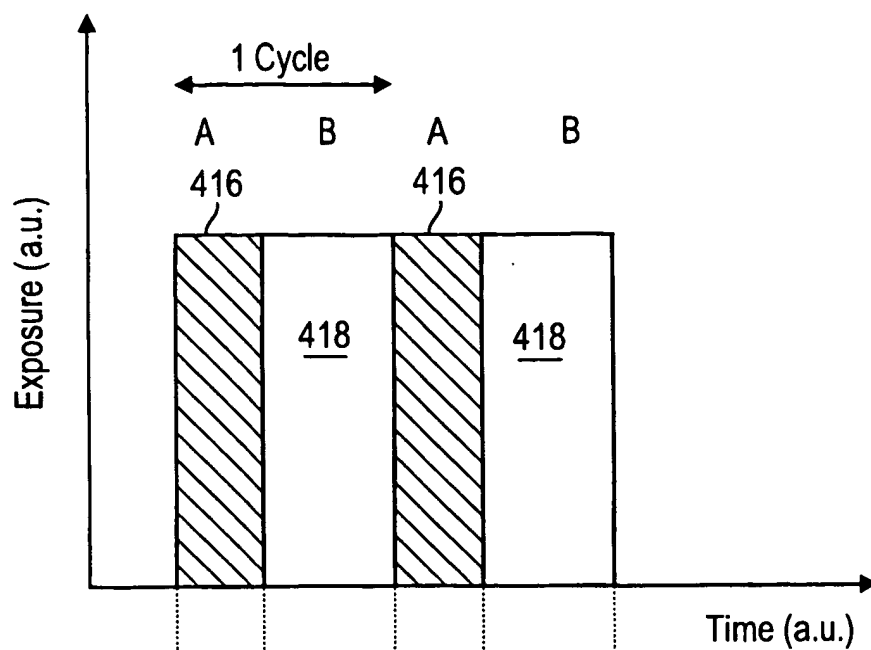


FIG. 37(b)

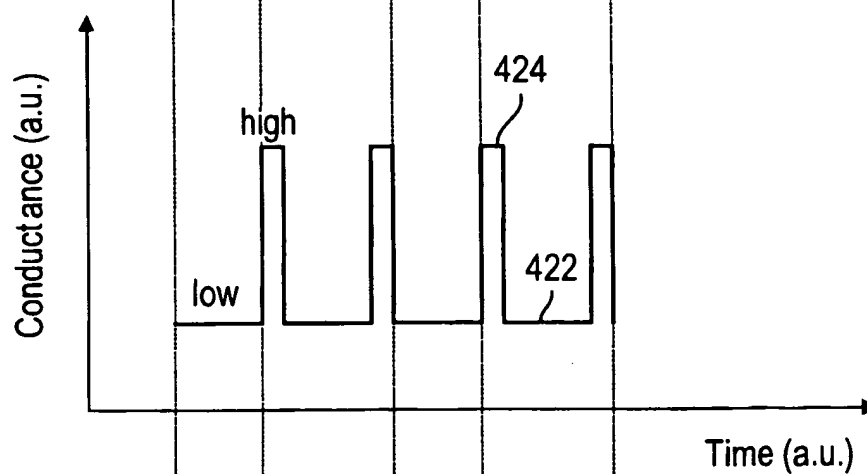
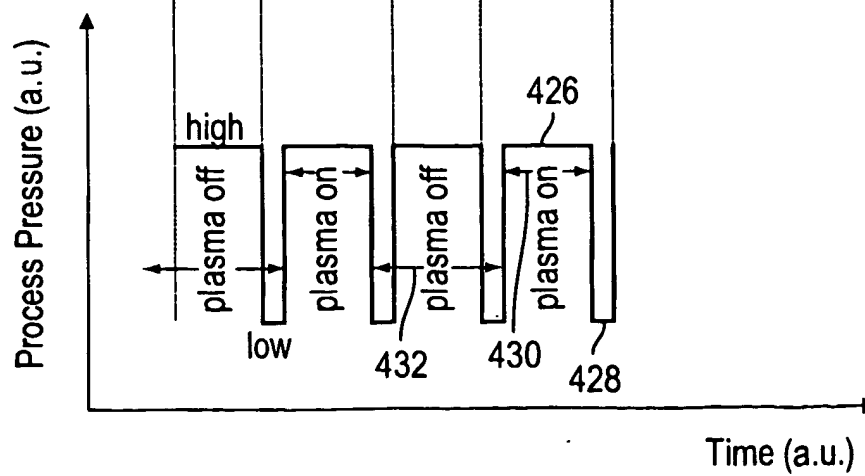


FIG. 37(c)



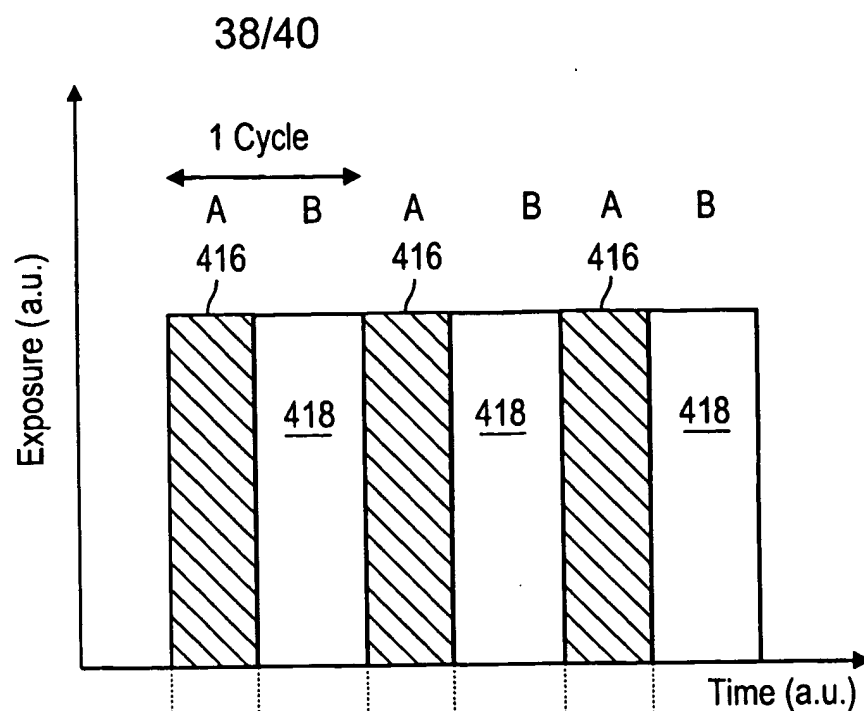


FIG. 38(a)

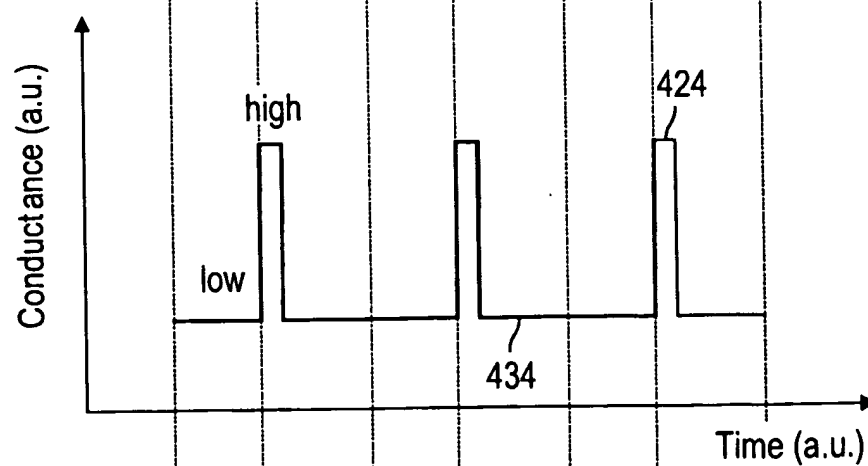


FIG. 38(b)

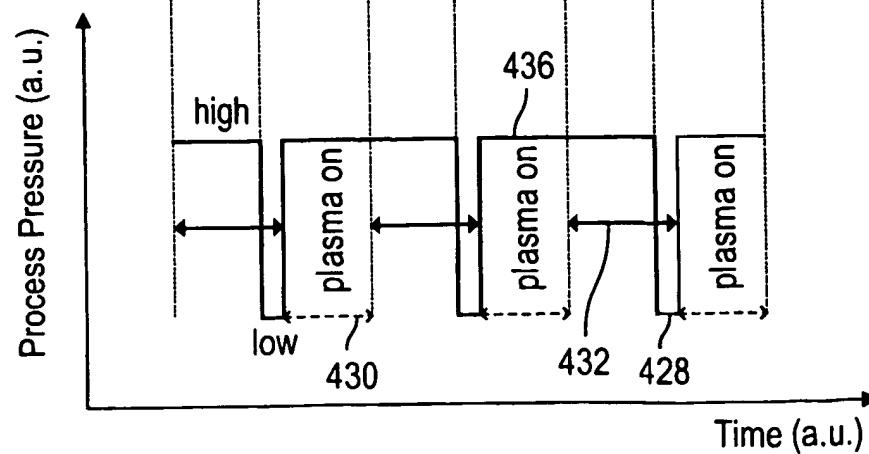


FIG. 38(c)

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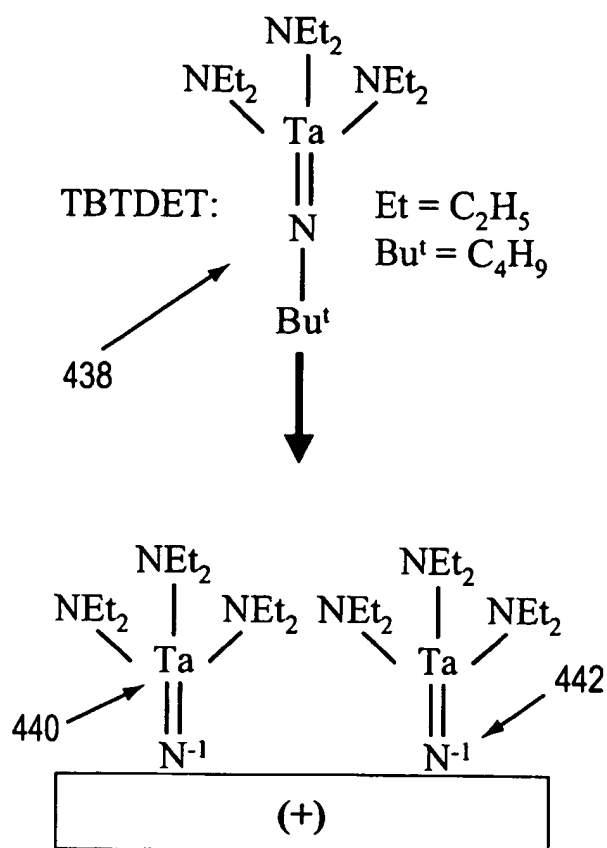


FIG. 39(a)

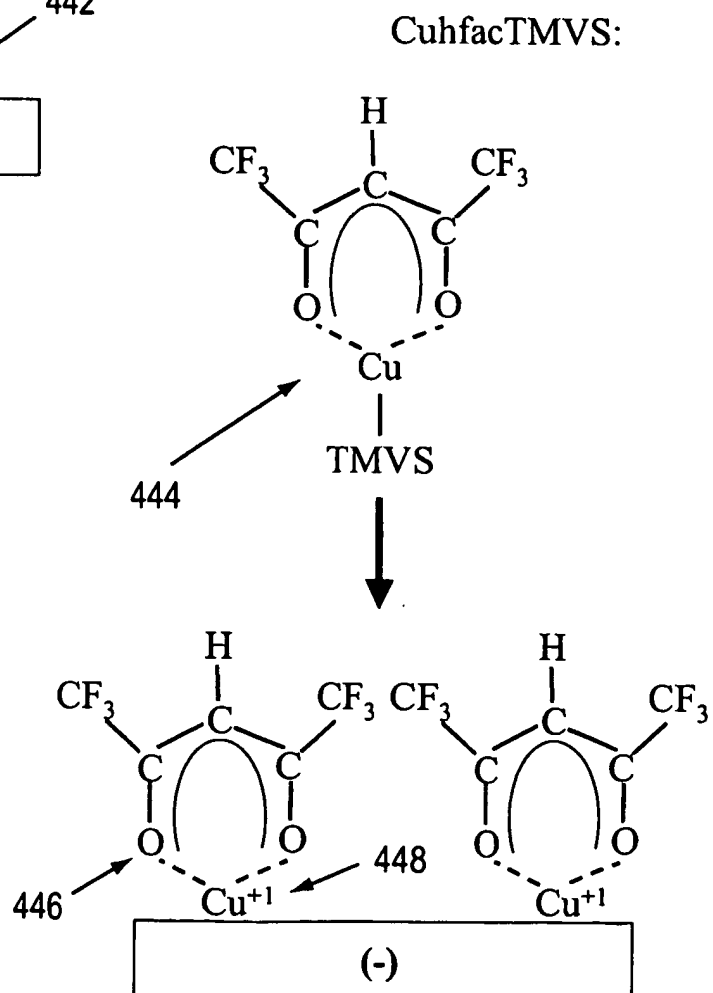


FIG. 39(b)

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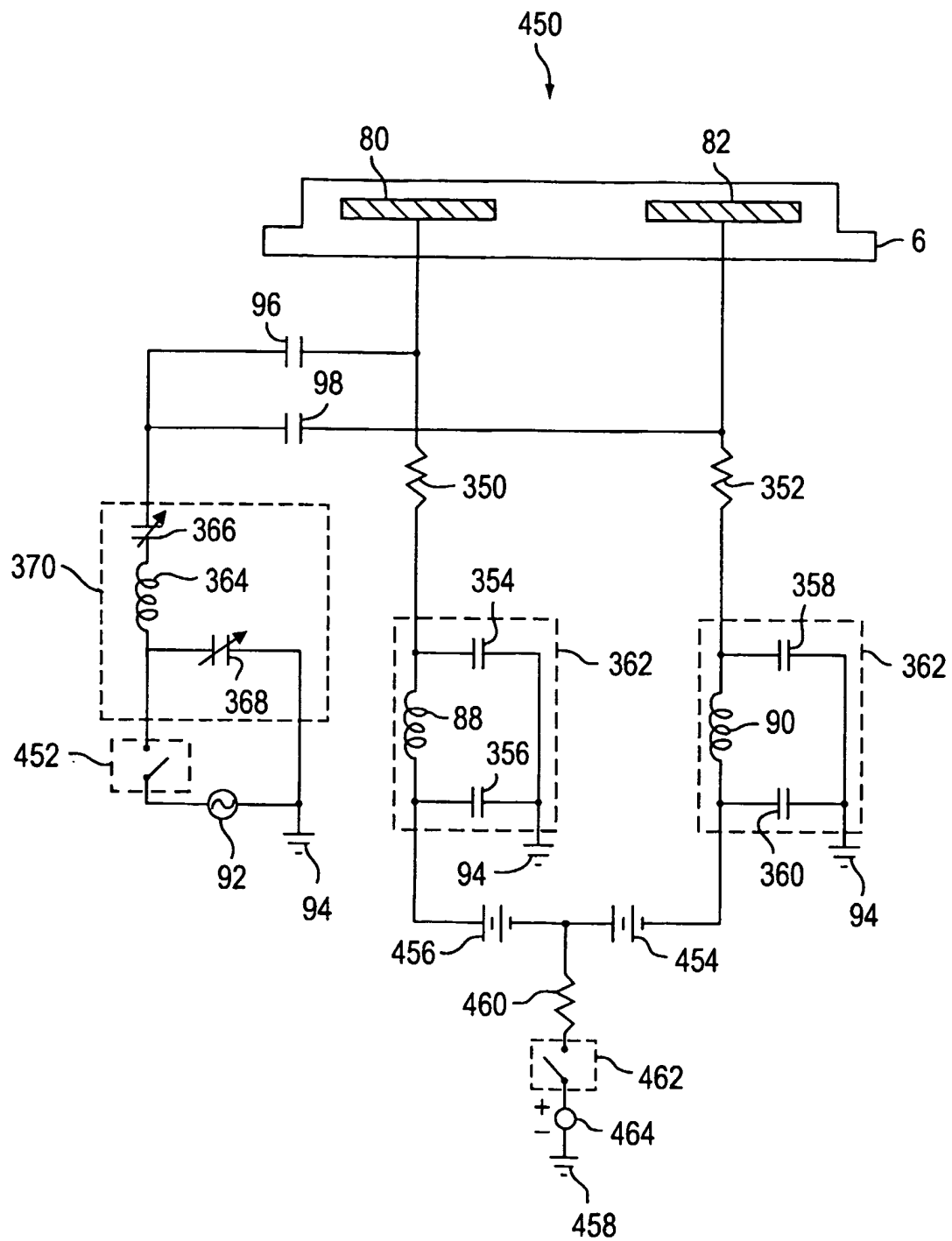


FIG. 40

PATENT COOPERATION TREATY

PCT

DECLARATION OF NON-ESTABLISHMENT OF INTERNATIONAL SEARCH REPORT

(PCT Article 17(2)(a), Rules 13ter.1(c) and Rule 39)

Applicant's or agent's file reference M-11466 WO	IMPORTANT DECLARATION	Date of mailing(day/month/year) 28/08/2002
International application No. PCT/US 02/ 09999	International filing date(day/month/year) 27/03/2002	(Earliest) Priority date(day/month/year) 05/04/2001
International Patent Classification (IPC) or both national classification and IPC C23C16/44 C23C16/455 C23C16/458 C23C16/46 C23C16/50		
Applicant ANGSTRON SYSTEMS, INC.		


This International Searching Authority hereby declares, according to Article 17(2)(a), that **no international search report will be established on the international application for the reasons indicated below**

1. ☐ The subject matter of the international application relates to:
 - a. ☐ scientific theories.
 - b. ☐ mathematical theories
 - c. ☐ plant varieties.
 - d. ☐ animal varieties.
 - e. ☐ essentially biological processes for the production of plants and animals, other than microbiological processes and the products of such processes.
 - f. ☐ schemes, rules or methods of doing business.
 - g. ☐ schemes, rules or methods of performing purely mental acts.
 - h. ☐ schemes, rules or methods of playing games.
 - i. ☐ methods for treatment of the human body by surgery or therapy.
 - j. ☐ methods for treatment of the animal body by surgery or therapy.
 - k. ☐ diagnostic methods practised on the human or animal body.
 - l. ☐ mere presentations of information.
 - m. ☐ computer programs for which this International Searching Authority is not equipped to search prior art.
2. ☒ The failure of the following parts of the international application to comply with prescribed requirements prevents a meaningful search from being carried out:

☐ the description
☒ the claims
☐ the drawings
3. ☐ The failure of the nucleotide and/or amino acid sequence listing to comply with the standard provided for in Annex C of the Administrative Instructions prevents a meaningful search from being carried out:

☐ the written form has not been furnished or does not comply with the standard.
☐ the computer readable form has not been furnished or does not comply with the standard.
4. Further comments:

SEE FURTHER INFORMATION

Name and mailing address of the International Searching Authority  European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Maria Van der Hoeven
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FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 203

In view of the large number and also the wording of the claims presently on file, which render it difficult, if not impossible, to determine the matter for which protection is sought, the present application fails to comply with the clarity and/or conciseness requirements of Article 6 PCT (see also Rule 6.1(a) PCT) to such an extent that a meaningful search is impossible. Consequently, no search report can be established for the present application.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.5), should the problems which led to the Article 17(2) declaration be overcome.

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